UNIVERSITY OF KWAZULU-NATAL

AN OPTIMISATION MODEL FOR THE MANAGEMENT OF TRANSFORMERS IN THE ESKOM EAST GRID TRANSMISSION SYSTEM

By

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ABSTRACT

The successes or failures one experiences in life depend greatly on the decisions that one makes. This is not only true in one's personal life but is also the case in the business environment. In this modern world, simple and complex decisions are the key elements for a business to be successful in the competitive global environment. Effective decision making is an intricate process. In Eskom it is important to integrate the technological and business aspects to support the decision making process. Research methodology provides one with the necessary tools to support this decision making.

The main focus of the study is the development of an Optimisation Model for the Management of Transformers in the Eskom East Grid Transmission Sysytem. In the Eskom Transmission system, there are a large number of power transformers which are the most expensive and strategically important component of the Transmission system.

There were three main objectives. The first objective included the forecasting of transformer failures using the forecasting techniques of moving average, weighted moving average, exponential smoothing and regression analysis. The second objective focused on the investigation of the re – location of the tap changer maintenance team to a new area using the mathematical and statistical methods of simulation and decision tree analysis. The third objective included the investigation of an inventory control and management model where the optimum number of spares pertaining to transformer units that should be made available was determined using the mathematical and statistical model called the economic order quantity. These objectives were then used to investigate the development of the optimisation model pertaining to transformers.

The results of the study concluded that the operating research techniques which included the forecasting methods and the economic order quantity models were suitable for research in Eskom. However it is important to note that the Eskom system and the environment in which transformers operate in is dynamic and has some factors that cannot be controlled. These factors

must be taken into consideration when the various models are used in the investigation of the optimisation model. The introduction of these external factors is beyond the scope of this study and is not included. It was concluded that the simulation and decision tree analysis could be used as an integral part of the optimisation model successfully.

The limitations that were highlighted included the integrity of the secondary data (sample size, the source of the secondary data, data quality and data governance), the limitations associated with forecasting, the limitations of the operations research, mathematical and statistical models and the fact that the Eskom network is dynamic. .

The recommendations included the application of the forecasting techniques and the inventory control model to a larger population size which was that of the transformers in the entire Transmission system. It was indicated that Eskom resources, time and money must be used to support the business's strategy to train and develop employees to an acceptable competency level. Future studies should include the factors that affect forecasting and the implementation of the inventory control model to increase the accuracy of the results. The introduction of these external factors is beyond the scope of this study and was not included in the models.

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CHAPTER ONE - INTRODUCTION

1.1 Introduction

Eskom touches the lives of all South Africans by providing electricity. Exciting innovations are outlined such as the growing use of technology – putting Eskom at the leading edge of global developments. The historical challenge facing industries such as Eskom is the balance between the technological and financial aspects of the business.

This chapter provides the background for the focus of the study which is, "An Optimisation Model for the Management of Transformers in the Eskom East Grid Transmission System". Eskom requires the seamless interlocking of several elements: steady and superior operational performance, proactive infrastructural investment, appropriate pricing structures and a level of customer service that sets it apart from its competitors as well as other utilities in the world. Collectively, Eskom has to integrate the technological and the business aspects more effectively and efficiently. Eskom needs to ensure continuity of supply to all it's customers in the most effective, efficient and cost effective manner.

This study explored three aspects namely transformer forecasting of failures, inventory control model and the re-location of the tap changer maintenance team. These results were then used in the preliminary investigation into the suitability of selected operations research techniques for use at Eskom.

The chapter outlines the details for the motivation, problem statement, focus, objectives and limitations for the study. It also outlines the application of various operations research, mathematical and statistical models that have been applied to achieve the objectives of the study.

1.2 Motivation for the Study

Simple and complex decisions are the key element to a business being successful in the competitively global environment. Research methodology is an innovative and practical way to provide businesses with the necessary tools to make these decisions. Effective decision making in this modern era is an intricate process. This is supported by three facts which are decisions have to be taken timeously, efficiently and effectively.

1.2.1 Case Study – East Grid in Eskom Transmission

The East Grid in Eskom Transmission is chosen as the case study to illustrate the use of modern operations research, mathematical and statistical forecasting models to implement a strategy for a real life problem.

The East Grid in Eskom Transmission is situated in Kwazulu - Natal and consists of four areas which are Pinetown, Ladysmith, Newcastle and Empangeni.

The Grid consists of various line functions which include Primary (HV) Plant, Secondary Plant and the Lines and Servitude Department. One of the aspects of Primary Plant is the substations which consist of different types of equipment. For the purpose of the study, one type of equipment which is transformers is chosen. Transformers step up or step down voltage as required. Transformers form an integral part of the network and the operation is dependent on the load that is required. Hence one has different voltage transformers which are rated at different loads. A 132/88/33 kV (voltage specification) rated at 250 MVA (load specification) costs approximately
R12, 5 million. Figure 1.1 is an illustration of the East Grid Transmission network.

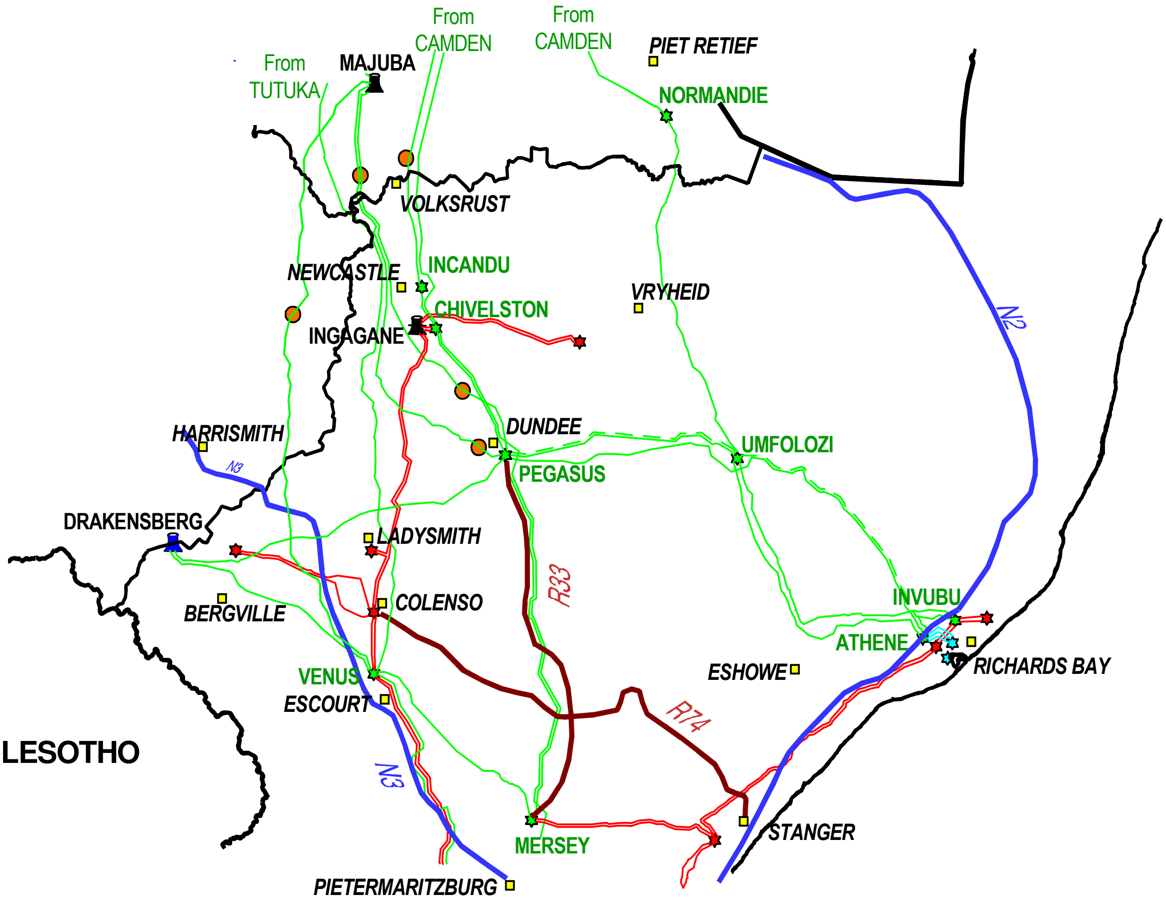

Figure 1.1: Graphical Representation of the East Grid Network

Adapted from 'East Grid Lines' 2009, CD-Rom, Eskom Transmission, Kwazulu - Natal, South Africa

Figure 1.1, is a graphical representation of the Lines and Servitudes of the East Grid Eskom Transmission. These lines are interconnected by substations and are fed off from the transformers at the different substations.

1.2.2 Prediction of Future Transformer Failures

Strategic Thinking means seeing ahead but one cannot see ahead unless one can see behind. A good vision of the future has to be rooted in the understanding of the past (Mintzberg & Lampel 1998). This is an indication that in order to strategise for the future it is important to analyse the past statistics, trends and behaviour of systems. The total number of Transmission transformer faults was of a great concern for Eskom.

With the current situation in Eskom where Eskom has reached its transfer capability it is important for Eskom to forecast for the future in an attempt to prepare and reduce load shedding due to unplanned outages. This means that the demand for electricity by Eskom's customers is greatly then the supply of electricity that Eskom can provide. Figure 1.2 is a photograph of a severe failure on a Transformer. This Transformer was completely destroyed by the fire that started because of a fault on the Transformer. Hence the study will include the forecasting of Transformer Failures which will have cost implications on the Optimisation Model developed.

Figure 1.2: Picture of a Transformer on Fire at Ariadne Substation in Eskom

Adapted from 'HVPlant' 2009, CD-Rom, Eskom Transmission, Kwazulu-Natal, South Africa

1.2.3 Inventory Planning and Control

While one can't bottle lightning, one can build rods (Hamel 2002, p.289). The basic purpose of inventory analysis in manufacturing and stock-keeping analysis in services is to specify (a) when items should be ordered and (b) how large the order should be. Recent trends have modified the simple questions of "when" and "how many". Inventory can be the most expensive and the most important asset for an organization.

Eskom uses the past failure history and maintenance history to determine the need for inventory. The failure history includes the failure rate and the failure modes. Eskom in its quest for perfection, identifies the number of failures, the reasons for failures, finds solutions, implements, monitors, controls, plans for the future and adheres to strict quality standards.

In Eskom the need for inventory for transformer spares was identified during the period 01 April 2003 to 07 March 2009 when numerous forced outages were experienced due to transformer failures and transformer faults. A forced outage is when a piece of equipment is taken out of service due to emergency conditions and not for planned maintenance. These outages impact on the continuity of supply to customers and have great cost implications. Furthermore the lead time for a transformer is 12 months hence the integrity of the system is threatened in the event of a transformer failure and in the event of unavailability of spares. Therefore it is imperative that an effective inventory control plan is in place in order to ensure the availability of spares.

Hence the study focuses on Inventory control of transformer spares.

1.2.4 Tap changer maintenance team

"Enterprises enjoying the greatest benefit from their performance management systems are much better at aligning their corporate, business unit and support strategies and this indicates that alignment produces synergies and also big benefits. Understanding how to produce this strategic alignment is crucial because this will be able to produce significant benefits for all types of businesses," Hough (2008, p.14). Here Hough highlights the importance of performance management. The movement or turnover of key personnel, reallocation of resources and other changes increase the difficulty of focusing without distraction.

During the implementation process of strategy, it is important that the implementation is continuously monitored to identify areas of efficiency or inefficiency, effectiveness or ineffectiveness. A company's vision, objectives, strategy and approach to implementation are never final; evaluating performance, monitoring changes in the surrounding environment, and making adjustments are normal and necessary parts of the strategic management process (Thompson & Strickland 1998, p. 16). This is important to create tight performance feedback loops.

This performance feedback will help refine efforts along all three dimensions – definition of longer term direction, deployment of aggressive near term operating initiatives and implementation of targeted initiatives (Hagel & Brown 2005, p.162).

The replacement cost of the Eskom Transmission asset base is calculated to be R50, 000 per MVA and the repair cost is 70% of this value, resulting in a replacement in excess of R6, 250 million or if repairable, in a repair cost of R4,400 million. The average age of transformers is just above the midlife (20 years) as they are at 24.6 years old (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

A non – severe failure is classified as a failure which results in a trip (interruption of supply to customers). The failure can be repaired on site and the plant can be returned to service. There exists a situation where the tap changer has to be repaired on site. In order to prevent severe and non – severe failures it is imperative that tap changer maintenance is carried out as required.

The tap changers are maintained by a sub – division of Eskom known as Rotek which is located in Johannesburg. The Rotek team is responsible for tap changer maintenance throughout South Africa. Due to this fact the availability of the teams to do work in the East Grid has posed a serious problem as on many occasions the teams have not been available, due to job commitments in other parts of South Africa.

The first problem identified with the centralization of the maintenance team in Johannesburg was the availability of the team for the work in the East Grid.

The second problem identified was the high cost of maintenance (labour costs and travelling costs).

Due to the problems associated with the availability and the high costs arising due to the centralization of the tap changer team in Johannesburg, the East Grid decided to explore the options of moving the team to Kwazulu-Natal as opposed to keeping them up in Johannesburg. Kwazulu - Natal is subdivided into four areas that include Pinetown, Empangeni, Newcastle and Ladysmith. The feasibility of moving the team to one of these four areas as compared to remaining in Johannesburg has been investigated.

Hence the study focused on the feasibility of moving the tap changer maintenance team to one of the four areas of the Kwazulu - Natal as compared to the team remaining in Johannesburg. Figure 1.3 is a photograph of a tap changer removed from a transformer during tap changer maintenance.

Figure1. 3: Picture of the internal component of a Tap Changer

Adapted from 'HVPlant' 2009, CD-Rom, Eskom Transmission, Kwazulu-Natal, South Africa

1.2.5 A Model for the Asset Optimisation of Transformers in Eskom

The motivation for the paper is the analysis of operational, maintenance (planned and abnormal), failure and financial statistics of transformers for the time period 1993 to 2007 using various operations research, mathematical and statistical models. The analysis involves the integration of all the data collectively and the investigation of an optimisation model for the management of transformers in the Eskom East Grid Transmission system.

1.2.6 Stakeholders that Benefit from the Study and Discipline Contribution

The research will then be utilised by the Primary (HV) Plant Senior Engineer to manage the Primary (HV) Plant budget. The East Grid in Eskom Transmission is responsible for the supply of electricity to BHP Billiton, Eskom Distribution and Ethekweni Municipality.

These are a few of the largest customers that Eskom supplies electricity to. Some of the companies that fall under BHP Billiton are Hillside Aluminium, Bayside, Newside and Richard Bay Minerals. Eskom bills BHP Billition for R 170 million in revenue on a monthly basis. The stakeholders that will benefit from the research that was concluded in this research paper is Eskom Transmission, Eskom Distribution, BHP Billiton, Ethekweni Municipality and all of Transmission's customers. The research will also provide benefit to the Financial and Primary Plant Departments of the East Grid. Another benefit of the study is the effective and efficient management of transformers as well as the implementation of an effective optimisation model.

1.3 Focus of the Study

The main focus is the development of an optimisation model for the management of transformers in the Eskom East Grid system. This has been achieved by the development of tools, methodologies and practices to manage the excessive costs incurred due to transformers more effectively hence increasing the business profit.

The focus is on the processes associated with operations research techniques and are tabulated as follows:

- A historical analysis of operational, maintenance (planned and abnormal), failure and business statistics of transformers for the time period 1996 to 2008 has been conducted.
- The use of operations research models used for forecasting techniques have been utilised to predict the future failures of transformers. The forecasting models that have been used include moving averages, weighted moving averages, exponential smoothing and forecasting time using regression analysis. This has impacted on the optimisation model as forecasting of future failures has been used to quantify costs associated with it.
- An inventory planning and control model for transformer spares has been developed. This has been done using the economic order quantity (EOQ) model. This model has impacted on the optimisation model.
- The strategy for the maintenance of transformer tap changer maintenance has been investigated. The aspect of the relocation of the tap changer team from Johannesburg to one of the four areas in the East Grid has been explored using modern mathematical and statistical models. These models include simulation and decision tree analysis. The effective management of the tap changer maintenance team results in the life extension of tap changers which have a domino effect. It results in the life extension of transformers which impact on the optimisation model.

The study integrates all the afore-mentioned objectives and the integration is used in the investigation of an optimisation model for the management of transformers in the Eskom Transmission East Grid system.

1.4 Problem Statement of the Study

The study focuses on "An Optimisaton Model for the Management of Transformers in the Eskom East Grid Transmission System". High demands on quality of supply, financial resource constraints, ageing of plant and the reduction of maintenance skills have impacted on the importance of transformer maintenance. Within the Transmission Grids there are a large number of power transformers which are the most expensive and strategically important components of any Transmission system. Their presence and operation are indispensable for guaranteeing a faultless power Transmission and Distribution network. Furthermore their loss can only be compensated through enormous financial, technical and operational efforts. Their operation exposes them to harsher than normal environments (Auditore 2008, p. 2).

1.5 Objectives

The main objective is the development of an optimisation model for the management of transformers in the Eskom East Grid Transmission system. This has been achieved by the development of tools, methodologies and practices to manage the excessive costs incurred due to transformers more effectively hence increasing the business profit.

The processes associated with achieving the main objective are listed below and form part of the objectives for the study:

- Objective One: A historical analysis of operational, maintenance (planned and abnormal), failure and financial statistics of transformers for the time period 1996 to 2008 is required.
- Objective Two: The objective is to use operations research models for forecasting techniques to predict the future failure rates of transformers. The forecasting models that have been identified to achieve this objective are the moving averages, weighted moving averages, exponential smoothing and forecasting time using regression analysis.
- Objective Three : The objective is the development of an inventory planning and control model for transformer spares which will be completed using the economic order quantity (EOQ) model.
- Objective Four: The objective is the assessment of the existing tap changer maintenance strategy and the development of a future and

more feasible strategy. The aspect of the relocation of the tap changer team from Johannesburg to one of the four areas in the East Grid will be investigated using modern operations research models. These models include simulation and decision tree analysis. This strategy impacts on the life span of the transformers.

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The study will integrate all the afore-mentioned objectives and will be used in the development of an optimisation model for the management of transformers in the Eskom Transmission East Grid system.

1.6 Hypotheses/Research Questions

1.6.1 Hypothesis

The study does not utilise the concept of a hypothesis but approaches the main objective using research questions.

1.6.2 Research Questions

The following research questions will be investigated:

1.6.2.1 What does the analysis of the operational, maintenance (planned and abnormal), failure and financial statistics of transformers for the time period 1996 to 2008 indicate?

1.6.2.2 What is the failure mode of transformers in Eskom?

1.6.2.3 What will forecasting techniques reveal about the prediction of future transformer failures?

1.6.2.4 What inventory planning and control methodology can be used to develop an inventory management plan?

1.6.2.5 Should the tap changer maintenance team be re – located from Johannesburg to one of the four areas?

1.7 Limitations of the Study

Some of the limitations of the studies are tabulated and discussed. These are discussed under the integrity of the Eskom data, the factors that affect forecasting, the limitations due to the operations research, mathematical and statistical models and the fact that the Eskom network is dynamic.

1.7.1 The Integrity of Eskom Data

1.7.1.1 Source of Data

The data from the Eskom databases Phoenix, SAP, TIPPS, TAMS, LIMMS and "Eskom HYPERWAVE" have been researched. The integrity of the data is dependent to a great extent on the processes that are implemented in Eskom. This includes the actual software and technology used. It also depends on the skills and competency of the Eskom personnel capturing the data and using the software. The introduction of the human element introduces an element of risk associated with the integrity of the data. The integrity of the data is also dependent on the time period that it takes to capture it. In Eskom Transmission, the occurrence of a failure of a transformer gives rise to a preliminary report which must be written and circulated within 24 hours of the failure. This report is then used to enter the initial information about the failure onto TIPPS. Recently a new database called TAMS has been implemented. This then prompts an investigation where the cause of failure, the circumstances surrounding the failure and the recommendations are investigated. A final report is then issued. The finalized information with respect to the cause, circumstances and the recommendations is then updated onto TIPPS or TAMS. These different processes have to be done within a specified period of time to ensure the integrity of the data captured.

1.7.1.2 Data Quality

Eskom has strict processes in place that ensure that the data captured is of a high quality. Furthermore there are processes and SLAs (time period for the different processes which are specified in a standard) in place that ensures that no data is lost and that incorrect data is not recorded. Furthermore the history of all transformer related information is available from 1996 until year to date. In 1998 the Information Technology processes for data capturing were first implemented. This information can be used for trending and benchmarking not only internally but externally as well. Furthermore there are various processes in place that audit the data to ensure that a high quality of data is captured and maintained. Despite these control measures that have been implemented to ensure a high quality of data, the systems are still prone to bugs either of a technological or human nature. These can have negative effects on the quality of data.

1.7.1.3 Data Governance

Data governance is an important functionality. Eskom has processes in place (databases, systems, audits, responsible and accountable people) that ensure that there is integrity and quality in the captured data. In the process of research large amounts of money is spent analyzing captured data in order to make important decisions associated with strategy, resources (material and people), technology and budgets. However there is still a possibility that data governance will be compromised due to software, human or process problems. This is illustrated in Figure 1.4.

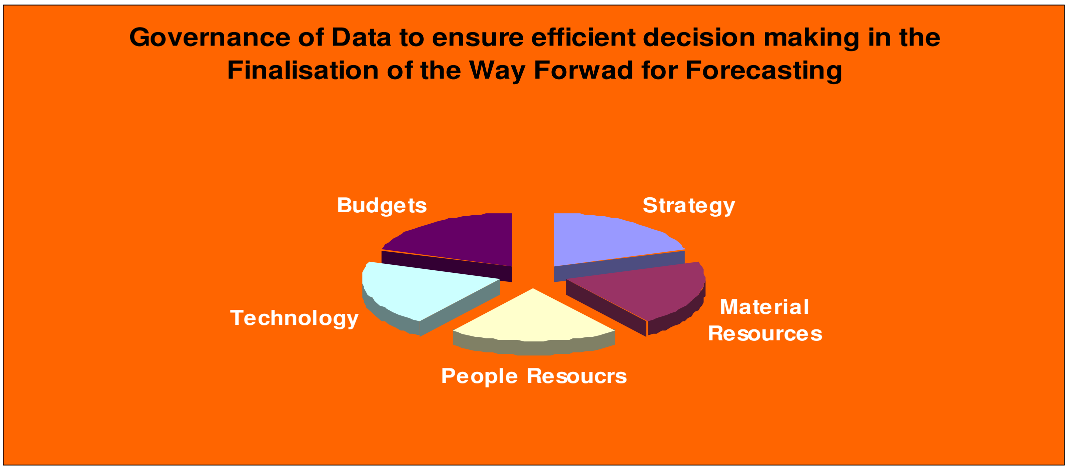

Figure 1.4: Graphical Representation of the Governance of data to ensure efficient and effective decision making.

In Figure 1.4, an assumption was made that are factors are weighted equally.

1.7.1.4 Sample Size and Application of Actual Data

The area for focus chosen for the study is the East Grid in Eskom Transmission in Kwazulu - Natal. There were limitations pertaining to the actual use of the secondary data. For the objective pertaining to the forecasting of future failures of transformers and the development of an inventory management tool, the entire population of transformers for all the

Grids in the Transmission network was chosen. The forecasting models could not be done on data pertaining to the East Grid only as there was insufficient data to analyse. The actual data and records was available however upon analysis it was found that there was no or an insignificant number of transformer failures in the East Grid to model on. The study focuses on severe transformer failures and the data in the East Grid was "zero" number of severe failures for most of the time period of 1996 to 2008. Hence a decision was taken to extend the study to the entire population of transformers in Transmission. The total number of 582 includes 505 transformers and 77 reactors.

1.7.2 Fore-casting in Eskom is Dependent on Various Factors

Forecast planning is extremely difficult and is subject to variables such as load shedding, summer demand, winter demand, material resources, technology, planned maintenance outages, emergency outages, spares, labour resources and skills.

The demand in winter is greater than in the summer period which results in increases in the loading on transformers hence "making them work harder" and increases the risks of failures. Furthermore planned and unplanned outages also increase the risk on the system and require transformers to be loaded even further. This contributes greatly to the life span of the transformers. This phenomenon is illustrated in Figure 1.5.

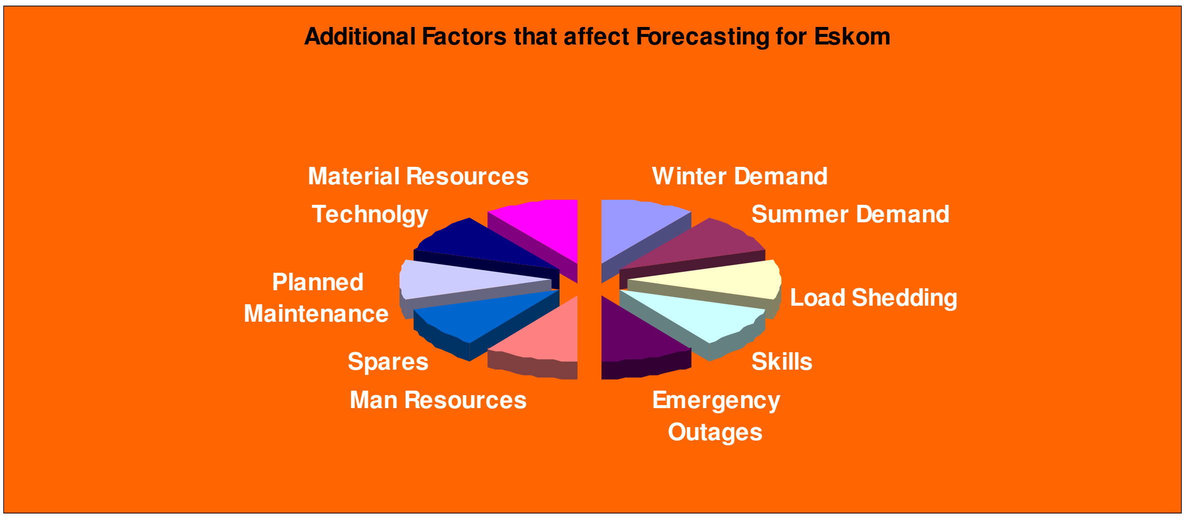

Figure 1.5: Factors affecting Forecasting planning

In Figure 1.5, an assumption has been made where the different factors have been weighted equally.

1.7.3 Limitations of Mathematical and statistical Models (Simulation and Decision trees)

1.7.3.1 Simulation

Another limitation identified in the study was some of the facts associated with simulation. The simulation was a long and complicated process. A trial and error approach was used that produced different solutions in repeated runs. All of the conditions and constraints had to be generated for the solutions that were examined.

1.7.3.2 Decision tree Analysis

It was a time-consuming process. All the possible alternatives had to be investigated before the best one could be chosen. Due to this there was always a possibility that all the options were not considered. This could have serious implications on the findings of the research.

1.8 Conclusion

The chapter provided an introduction to the study which focussed on an optimisation model for the management of transformers in the Eskom East Grid Transmission system. The study focused on aspects associated with asset management of transformers in Eskom.

The investigation of the processes associated with operations, maintenance (planned and abnormal), failure statistics, capital projects, financial statistics, forecasting of future transformer failures and inventory planning and control for transformer spares and the strategy for the location of the transformer tap changer maintenance teams has been conducted. The study included the analysis of the results of the modelling and this was used in the study.

The chapter also outlined the stakeholders who will benefit from the research. The limitations to the study were also highlighted. The limitations that were highlighted included the integrity of Eskom data, the limitations associated with the forecasting techniques, the limitations associated with the operations research, mathematical and statistical models and the fact that Eskom network is dynamic.

The constantly changing environment associated with demand and supply capabilities, resources (man, money and material), the network system, weather and environmental factors and faults on the system also provides a hurdle in the compilation of the Optimisation Model.

Chapter One provides the background for Chapter Two which is the Literature Review of the study.

CHAPTER TWO – REVIEW OF LITERATURE

2.1 Introduction

Chapter Two is the Literature Review of the study. The review has been conducted on the available literature pertaining to the operations research, simulation and decision tree analysis models. General background information on the company, Eskom, which is linked to the research topic, has been included in this chapter. Literature on forecasting methods, inventory management, standards, procedures, modification and technical instructions have been researched and listed accordingly. The review finally provides two case studies pertaining to oil leaks and corrosion problems in the East Grid.

The Literature Review provides the theoretical knowledge that is required for the study.

2.2 General Theory on Operations research, Simulation and Decision tree Analysis

2.2.1 General Theory on Operations research

Most operations research studies involve the construction of a mathematical model. The model is a collection of logical and mathematical relationships that represents aspects of the situation under study. Models describe the important relationships between variables; include an objective function with which alternative solutions are evaluated, and constraints that restrict solutions to feasible values.

Although the analyst would hope to study the broad implications of the problem using a systems approach, a model cannot include every aspect of a situation. A model is always an abstraction that is of necessity simpler than the real situation. Elements that are irrelevant or unimportant to the problem are to be ignored; hopefully leaving sufficient detail so that the solution obtained with the model has value with regards to the original problem.

Models are both tractable, capable of being solved, valid and representative of the original situation. These dual goals are not always attainable.

It is generally true that the most powerful solution methods can be applied to the simplest, or most abstract, model (Render, Stair & Hannah 1997, 2000, 2003, 2006, pp. 193 – 200).

The Simulation and the Decision tree Analysis models have been used in this study to find the most feasible solution for the problem identified.

2.2.2 General Theory on Simulation

Of all the analytic methods that comprise operations research, simulation, stands in sharp contrast to mathematical programming algorithms and stochastic models. With simulation, the analyst creates a model of a system that describes some process involving individual entities such as persons, products or messages. The components of the model try to reproduce, with varying degrees of accuracy, the actual operations of the real components of the process. Most likely the system will have time varying inputs and time varying outputs that are affected by random events. The components of the simulation are interconnected and can often be viewed as a network with complex input – output relationships. Moreover, the flow of entities through the system is controlled by logic rules that derive from the operating rules and policies associated with the process being modelled.

Because the model takes the form of a computer program, which operates as a facsimile of its real – world counterpart, it is much less restricted than analytical modes. Within the limitations of the input and output interfaces, a skilled programmer can duplicate with a high level of accuracy, most systems that can be observed and rationalized. Because of this capacity for detail, simulation has become a very popular method of analysis. Particularly appealing is its ability to model random variables with arbitrary probability distributions and systems that have a variety of interacting random processes. Modern simulation languages are very powerful tools, allowing the user to create representations of complex systems (Render, Stair & Hannah 1997, 2000, 2003, 2006, pp. 193 – 200).

Simulation has evolved into a mature discipline that is now one of the most widely used techniques in Operations research.

2.2.3 General Theory on Decision tree Analysis

Decision trees are excellent tools for helping one to choose between several courses of action.

They provide a highly effective structure within which one can lay out options and investigate the possible outcomes of choosing those options. They also provide assistance to one to form a balanced picture of the risks and rewards associated with each possible course of action.

A decision tree shows the alternative actions that a decision maker can follow, as well as, the events that can arise, by means of branches. They incorporate points where decisions must be made and points indicating the events that follow decisions: shown as nodes. These choices and decisions are illustrated as symbols in Figure 2.1.

- Here a choice must be made.

- Event node

Figure 2.1: Explanation of symbols in a Decision tree Diagram

Adapted from Lind, D.A, Marchal, W.G. & Wathen, S.A 2008, Statistical Techniques in Business and Economics with Global Data Sets, The McGraw-Hill Companies, New York, pp. 754 -755.

The choices between the various alternatives are made by evaluating the decision tree backwards which is from right to left on the diagram. An alternative that is chosen is shown by two parallel lines on the decision tree.

One must remember that the decision tree does not provide a final answer, but rather highlights a particular strategy.

2.2.4. The Advantages and Disadvantages of Simulation and Decision tree Analysis

The advantages and disadvantages of simulation and decision tree analysis have been researched and are listed (Render, Stair & Hannah 1997, 2000, 2003, 2006, pp. 201 -205).

2.2.4.1 The Advantages of Simulation

- It is relatively straight forward and flexible.
- Recent advances in software make simulation models very easy to develop.
- It can be used to analyze large and complex real-world situations that cannot be solved by conventional quantitative analysis models.
- Simulation allows what-if types of questions. Managers like to know in advance what options are attractive. With a computer, a manager can try out several decisions within a matter of minutes.
- Simulations do not interfere with the real - world system. It may be too disruptive, for example, to experiment with new policies or ideas in a hospital, school or manufacturing plant. With simulation, experiments are done with the model, not on the system itself.
- Simulation allows us to study the interactive effect of individual components or variables to determine which ones are important.
- "Time compression" is possible with simulation. The effect of ordering, advertising or other policies over many months or years can be obtained by computer simulation in a short time.
- Simulation allows for the inclusion of real – world complications that most quantitative analysis models cannot permit.

2.2.4.2 The Disadvantages of Simulation

- Good simulation models for complex situations can be very expensive. It is often a long and complicated process to develop a model. A corporate planning model, for example, may take months or even years to develop.

- Simulation does not generate optimum solutions to problems as do other quantitative analysis techniques such as economic order quantity, linear programming, or PERT. It is a trial and error approach that can produce different solutions in repeated runs.
- Managers must generate all of the conditions and constraints for solutions that they want to examine. The simulation model does not produce answers by itself.
- Each simulation model is unique. Its solutions and inferences are not usually transferable to other problems.

2.2.4.3 The Advantages of Decision tree Analysis

- Decision trees are valuable for evaluating the different capacity expansion alternatives when demand is uncertain and sequential decisions are involved.
- They are excellent larger decision problems particularly when one decision has to be made before other decisions are made.

2.2.4.4 The Disadvantages of Decision tree Analysis

- It is time-consuming as all possible alternatives have to be pursued before the best one can be chosen.
- Expected payoffs have to be stipulated before the model can be drawn out.

2.3 Forecasting and Load shedding in Eskom

One of the major contributors to achieving this effectively is the use of forecasting. With the introduction of load shedding due to Eskom reaching it's transfer capability, it is important for Eskom to do an analysis of it's abnormal situations in an attempt to not only use the past history to forecast for the future but it also imperative that Eskom learns from the past to ensure that it will be able to provide continuity of supply to it's customers and reduce load shedding to an extent where it is non-existent.

In the 1970’s and 1980’s Eskom conformed to the culture of South Africa at the time. It built power stations to the best of its ability and delivered electricity to a small number of large customers. Production was everything. Now Eskom’s focus has shifted to becoming a service organization, geared to finding out what the customer wants and providing it. With the introduction of government policies, procedures and government regulation, Eskom was forced to shut down vital power plants which has been one of the reasons for Eskom reaching it’s transfer capability with the growing demand of electricity (‘Eskom Executive Information’ 2009, Eskom Transmission, viewed 01 August 2009, <http://intranet.eskom.co.za/powerzone/main800x600.htm>).

2.3.1 Eskom’s Vision and Mission Statement

The Vision Statement for Eskom is, “Together building the powerbase for Sustainable Growth and Development”. The Mission Statement is, “To sustain, operate and maintain Reliable Transmission Networks in South Africa”. The values of Eskom are Integrity, Customer Satisfaction, Innovation and Excellence (‘Eskom Executive Information’ 2009, Eskom Transmission, viewed 01 August 2009, <http://intranet.eskom.co.za/powerzone/main800x600.htm>).

2.3.2 Industry Analysis, Comparison to Electricity Utilities in other Countries and Success Factors

A Market survey was done where it was found that Eskom provided the cheapest Electricity in the world. The average cost of Electricity sold in 2007 was 16, 09 cents per K/Wh (‘Eskom Executive Information’ 2009, Eskom Transmission, viewed 01 August 2009, <http://intranet.eskom.co.za/powerzone/main800x600.htm>).

Eskom was benchmarked in 2000 against 20 other electric utilities that are also tasked with the operation and maintenance of Transmission Grid. The utilities benchmarked were from countries such as New Zealand, Canada, Australia, Spain, Poland, Sweden. The electric utilities were benchmarked on various financial, technical, productivity and safety measures. In total there were 20 measures against which Eskom was benchmarked (‘Eskom

Executive Information' *2009*, Eskom Transmission, viewed 01 August 2009, <http://intranet.eskom.co.za/powerzone/main800x600.htm>).

ESKOM performed as a top performer or among the top performers in the areas of:

- Transmission operating costs/MWh delivered ($)
- Transmission operating costs/transmission employees.
- Transmission revenue/transmission assets.
- Number of industrial accidents/transmission employees.
- Number of major disturbances due to transmission.

ESKOM performed the worst in the areas of:

- Operating profit/total employees
- Total number of transmission faults/100km
- Total of Transformer Failures

2.3.3 Crisis Management – Using Forecasting

John Sterling (2003) has shown that managers need to confront the crisis when they formulate and evaluate their strategic options. Using all key aspects such as resilience, being proactive, learning how to manage a crisis, the organisation can reach new heights and ensure that the damage caused is minimal and contained. This can be achieved by forecasting.

2.4 Mathematics and Statistical Forecasting Methods

There are four statistical forecasting methods that will be used to forecast the future failure of transformers (Douglas, Marchal & Wathen 2008, pp. 602 – 633).

The methods that will be used are:

- Moving averages
- Weighted moving averages
- Exponential smoothing
- Forecasting time using regression analysis

2.4.1 Moving averages

The Moving average is calculated using the following equation:

Moving average = ∑ Most Recent Data / n
Where: Most Recent data = the no. of Transformer Failures
n = number of variables used

In the calculations that will be computated for the forecasting of transformer failures, a three period moving average will be used. This requires that the historical data of the previous three averages be used to forecast the fourth one. The forecast error and the forecast error squared will then be calculated. In the moving average all the different variables are weighted equally (Douglas, Marchal & Wathen 2008, pp 606 – 609, 633).

2.4.2 Weighted Moving averages

The second forecasting method to be used is the weighted moving average where the data is weighted. The more recent data is given a higher weighting. The further away the data is when it comes to time periods, the less reliable the data is in terms of forecasting. Hence the data for the most recent time periods are given a higher rating. The calculations of the weighted moving average are similar to the calculations of the moving average where the moving average calculations are used.

The weighted moving average is calculated using the following equation:

Weighting Moving average = ∑ Most Recent Data / n
Where: Most Recent data = the no. of Transformer Failures
n = number of variables used
Recent Data = Weighted Data Variables

The calculated weighted average is then used in the moving average equations and the forecast values and forecast errors are calculated (Douglas, Marchal & Wathen 2008, pp. 602 – 612).

2.4.3 Exponential smoothing

The third forecasting method used is that of exponential smoothing.

2.4.3.1 Important Information Pertaining to Exponential smoothing

Exponential smoothing is a statistical method which ensures that the values calculated are more synchronized by removing fluctuations. There are four components to a time series the trend, the cyclical variation, the seasonal variation and irregular variation. The trending of past history data for a company follows different patterns. These different patterns are determined by various factors which results in cyclical variation, seasonal variation and irregular variation.

In cyclical variation a typical business cycle consists of a period of prosperity followed by periods of recession, depression and then recovery. This usually occurs over time periods of longer than a year.

Seasonal variation occurs when sales and production fluctuate with the seasons. These are patterns of change in the time series within a year. These trends repeat themselves each year.

In irregular variation, analysts subdivide the irregular variation into episodic and residual variations. Episodic fluctuations are unpredictable but they can be identified. The initial impact on the economy of a major strike or war can be identified but the strike or war cannot be predicted.

The exponential smoothing is calculated using the following equation:

$$F_{t+1} = \alpha Y_t + (1 - \alpha) F_t$$

Where: F_{t+1} = Forecast of the time series for t + 1

Y_t = Actual value of the time series in period t

F_t =Forecast of the time series for period t

α = smoothing cos tan t, ($0 \leq \alpha \leq 1$)

Assume $\alpha = 0, 2$

An assumption for the value of α was determined by a trial and error method. This was done by the substitution of various values between 0 and 1 for alpha. The value that resulted in the smallest forecasting error was chosen.

After episodic fluctuations are removed, the remaining variation is called residual variation. These are unpredictable and cannot be identified. However neither episodic nor residual variation can be predicted into the future. Exponential smoothing is used to remove these fluctuations thereby synchronizing the data (Douglas, Marchal & Wathen 2008, pp. 613 – 617).

2.4.3.2 The Mean Average Deviation of Forecast Error and Forecast Error Squared

Management decisions have to take into account that all three different types of variations namely cyclical, seasonal and irregular are experienced, when analysis of Eskom forecasted data is done.

In cyclical variation, there are fluctuations in the business cycle due to periods of prosperity, recession, depression and then recovery. This is relevant as consumers use different amounts of electricity in the different time periods. Hence the demand changes and this affects forecasted values. This usually occurs over time periods of longer than a year (Douglas, Marchal & Wathen 2008, pp. 618 – 619).

In seasonal variation, the demand for electricity changes during the different seasons in the year. In summer the demand for electricity is less than the demand for electricity in winter. This has been verified by studies of previous data by Eskom. These trends almost repeat themselves each year. Hence management will have to take this into account. When the demand increases, the existing transformers have to be loaded more than the normal loading and this stresses the equipment which invariably can lead to a failure.

Irregular variation also has to be taken into consideration when forecasting for Eskom. Episodic fluctuations due to bird faults on the lines results in the tripping of the lines and this requires certain transformers to supply more load then they normally do. Hence this also results in stressing the transformers. These are unpredictable but they can be identified. There are also instances where staff maintain the transformers at a very low standard and this results in failures when the transformer is returned to service. These are classified as human errors and incorrect maintenance practices.

Residual variation is also very important and an example of this is the weather. The effectiveness of the weather forecasting has been proved not to be a 100 percent efficient. There have been past occurrences were unpredicted weather conditions have resulted in the faulting of equipment and this has resulted in failures.

This analytical statistical method is very important and is used by management in their forecasting at Eskom. The aforementioned factors that can be used to remove fluctuations in this method are illustrated in Figure 2.2.

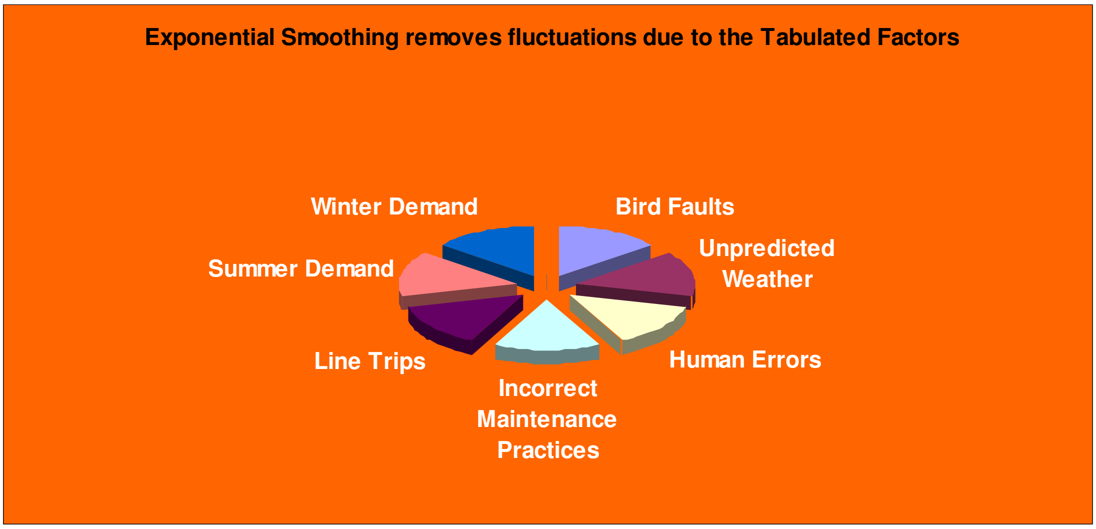

Figure 2.2: Exponential smoothing removes fluctuations due to the tabulated factors

In Figure 2.2, an assumption has been made where all factors have been weighted equally.

2.4.4 Regression analysis

2.4.4.1 Definition of Regression analysis

Regression analysis is used to predict the value of one variable on the basis of another variable. The technique is very useful; however, it involves developing a mathematical equation that describes the relationship between the variables to be forecast, which is called the dependent variable (Douglas, Marchal & Wathen 2008, pp. 620 – 632).

2.4.4.2 Determination of the Relationship Equation

The equation of a straight line graph is of the form **y= a + bx,** where

y = equation of a linear graph

a = y-intercept

b = gradient (slope)

x = x-intercept

a + b will determine the number of failures one will expect to have.

$$b = \frac{n\sum xy - (\sum x)(\sum y)}{n(\sum x^2) - (\Sigma x)^2}$$

a = y – bx is the test for linearity.

Using the equation a and b

$$a = \frac{\sum y - b(\sum x)}{n}$$

a = y – bx

Re-substituting into the equation (y = a + bx), and by the substitution of the time period for the value of x, one is able to forecast the number of transformer failures that one expects to have in a given period of time in the future.

2.4.4.3 The Standard Error of Estimate

The standard error of estimation is the estimated standard deviation of the error in the method used. It estimates specifically the standard deviation of the difference between the measured or estimated values and the true values. The true value of the standard deviation is usually unknown and the use of the term standard error carries with it the idea that an estimate of this unknown quantity is being used. The standard error also carries the notion that it measures, not the standard deviation of the estimate itself, but the standard deviation of the error in the estimate, and these can be very different.

The standard error of estimate is defined by the following equation:

$$\mathbf{S_e} = \sqrt{\frac{\sum y^2 - a\sum y - b\sum xy}{n-2}}$$

The total of the individual errors must be equal to zero, in order to test if the values of x and y are correct.

Therefore Y = a + b x + ε

Where ε, is the error variable and represents all the variables, measurable and immeasurable, that are not part of the model.

2.4.4.4 Coefficient of Determination and Correlation

Correlation analysis refers to a group of techniques that are used to measure the association between two variables. The coefficient of correlation describes the strength of a linear relationship between the independent (X) and dependent (Y) variables. Designated by **r**, the coefficient correlation which is often referred to as the Pearson's correlation coefficient can assume any value from -1.00 to +1.00 inclusive.

A coefficient correlation (r) of -1 indicates a perfect negative linear correlation between the two variables. All the data points will lie on a straight line, but in an inverse direction (i.e. as X increases, Y decreases and vice versa).

A coefficient correlation of +1 indicates a perfect positive linear correlation between the two variables. All data points on a scatter graph will lie in a straight line. If there is absolutely no relationship between the two sets of variables Pearson's r is zero. The coefficient of determination is the proportion of the total variation in the dependent variable Y that is explained by, or accounted for, by the variation in the independent variable X.

It is computed by squaring the coefficient correlation i.e. Coefficient of determination = r^2 and it measures the proportion or percentage of the total variation in Y as explained by the regression.

The coefficient of determination is defined by the following equation:

$$\mathbf{r^2} = \frac{a\sum y + \sum xy - n\bar{y}}{\sum y^2 - ny}$$

The coefficient of correlation is defined by the following equation:

$$r = \sqrt{\text{coefficient of determination}}$$

2.5 Inventory Planning and Control Literature

2.5.1 General Information pertaining to the Economic order quantity (EOQ).

Economic order quantity (EOQ) is used to determine how much to order. Render, Stair & Hanna (2006, pp. 193 – 200) have shown that the following assumptions are made:

- Demand is known and constant.
- The lead time, that is the time between the placement of the order and the receipt of the order, is known and constant.
- The receipt of inventory is instantaneous. This means that the inventory from an order arrives in one batch, at one point in time.
- Quantity discounts are not possible.
- The only variable costs are the cost of placing an order, ordering cost, and the cost of holding or storing inventory over time, holding or carrying cost.
- Orders are placed so that stock outs or shortages are avoided completely.

The theory states that when the EOQ assumptions are met, costs are minimized when the annual ordering cost (D/Q x Co) = annual holding cost (Q/2 Ch) where:

D = Annual Demand in units for inventory item

Q = Number of pieces to order

Co = Ordering cost of each order

Ch = Holding or carrying cost per unit per year

Hence EOQ (Q*) can be calculated when:

D/Q x Co = Q/2 x Ch

Solving for Q, the Economic order quantity is defined by the following equation:

$$\textbf{EOQ = Q* =} \sqrt{\frac{2D\mathrm{Co}}{\mathrm{Ch}}}$$

Adapted from Render, B, Stair RM & Hanna, ME 1997, 2000, 2003, 2006, Quantitative Analysis for Management, 9th Edition, Pearson Prentice Hall, New Jersey, pp. 193 – 200, 201 – 205, 216 -217,

2.5.2 General Information pertaining to when an Operation should replenish its inventory and When to Order?

2.5.2.1 Reorder Point System

Now that the determination of how much to order is complete, it is imperative to know when to order. The time between placing and the receipt of an order, is called the lead time or delivery time. This is often a few days or few weeks. Inventory must be available to meet this demand during this time. Thus the, "when to order", decision is usually expressed in terms of a reorder point (ROP), the inventory level at which the order should be placed (Render, Stair & Hanna 2006, pp. 200 - 201). Reorder Point (ROP) = demand per day (d) x lead time for a new order in the system (L).

2.5.3 The Control of Inventory

The control of inventory is either achieved by physical stock-taking or by the use of Management Information Systems to maintain adequate control over each inventory item thus ensuring that accurate records are kept of stock on hand. Maintaining inventory through counting, placing orders and receiving stock takes personnel time and costs money.

2.5.4 ABC Inventory Planning

Every inventory system must specify when an order is to be placed for an item and how many units to order. In most situations involving inventory control, there are so many items involved that it is not practical to monitor each and every item. To get around this problem the ABC classification scheme divides inventory items into three groupings: high dollar volume (A), moderate dollar volume (B) and low volume dollar (C). Dollar volume is a measure of importance; an item low in cost but high in volume can be more important than a high cost item with low volume.

The purpose of classifying items into groups is to establish the appropriate degree of control for each item. For example Class A may be more clearly controlled with weekly ordering, B items may be ordered biweekly and C items may be ordered monthly or bimonthly (Render, Stair & Hanna 2006, pp. 216 - 217).

2.5.5 Inventory Accuracy

Every production system must have agreement, within some specified range, between what the records says is in inventory and what actually is in inventory. There are many reasons why records and inventory don't agree. For example, having an open stockroom area allows items to be removed for both legitimate and unauthorized purposes. The legitimate removal may have been done in a hurry and simply not recorded. Sometimes parts are misplaced, turning up months later. Parts are often stored in several locations, but records may be lost or the location is recorded incorrectly.

Sometimes stock replenishment orders are recorded as received, when in fact they never were. Occasionally, a group of parts is recorded as having been removed from inventory, but the customer order is cancelled and the parts are replaced in inventory without cancelling the record. To keep the production system flowing smoothly without parts shortages and efficiently without excess balances, it is important that inventory records are accurate.

2.5.6 The Role of Information Technology (IT) in Inventory Management

The ability of firms to significantly reduce inventories while still providing high levels of service is due largely to the advances in information technology. IT allows manufacturers like Procter and Gamble to work much more closely with retailers like Wal-Mart. Point of Sale (POS) equipment records unit product sales, which are immediately sent electronically to the manufacturer. Radio Frequency ID (RFID) tags now allow companies to know the exact location of every item in inventory, and as the cost of RFID drops, companies will be able to afford to put these tags on more products.

Bar-coding technology allows firms to keep track of every item from the time it is received to when it is sold. As a result, the inventories of more and more products are being managed on a perpetual inventory basis instead of fixed-interval basis, allowing managers to reduce inventory levels.

Enterprise resource planning (ERP) systems like SAP totally connect all of the functional areas within a company, and even between companies in a supply chain. This electronic network allows orders to be quickly processed and products to be delivered faster, resulting in lower inventories. These systems also facilitate build to order processes, which significantly reduce work in process inventories and virtually eliminate finished goods inventory (O'Brien & Marakas 2008, p. 296).

2.5.7 Example of the Ultimate Inventory controlling System – Philips Semi-Conductors

The use of RFID technology in the retail industry has been increasing. Companies are finding that RFID adoption is easier in the manufacturing sector and upstream in the supply chain in areas such as asset tracing, inventory management and security related government driven applications such as international air travel. Companies that are adopting this system are Wal-Mart (USA), Marks and Spencer (UK), Philips Semiconductors, IBM (UK, Sweden). "Philips Semiconductors" consists of 20 large manufacturing and distribution facilities with approximately 36 000 employees and hundreds of sales organizations spread over 60 countries.

The previous barcode system involved manually scanning the bar code to capture inventory information using a barcode reader with a direct line of sight to each carton. This was a time consuming process. There were discrepancies between the actual product status and the status recorded in the ERP (Enterprise Resource Planning) system. This caused problems for both customers and staff who shared and acted upon erroneous information. Philips Semiconductors re-engineered this process. The embedded miniature antennae, RFID tags send bits of essential stored information as signals to a receiver that reads and forwards the information to a server. The server then automatically updates the company's ERP system.

A real time connection is established between its manufacturing and distribution centres and its ERP application. RFID tags also enable more specific criteria to be used to track products which allow them to manage the inventory more efficiently. The tags can be read from any angle. This provides more flexibility on the managing of physical space from a distance.

As a result of re-engineering the supply chain processes, Philips has increased its inventory turns, improved stacked lead time, optimized space utilization, enhanced delivery reliability and warehouse efficiency and improved customer service. It also generates customer invoices much more quickly, resulting in shorter billing cycles by reducing the information latency in its ERP system ('NXP Semiconductors' 2007, Wikipedia, viewed on the 14 September 2007, <http://en.wikipedia.org/wiki/NXP_Semiconductors >).

2.6 Literature Review of Eskom Standards, Procedures, Modification and Technical Instructions

The following standards have been reviewed and used in the study. The standards are as follows:

- Eskom Transmission 2006, *ABB Tap changer Modification Instruction*, TM141- 15 Rev 0, Eskom, South Africa.
- Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa.
- Eskom Transmission 2006, *Routine Maintenance of Transmission Power transformers and Reactors*, TS141-138 Rev 0, Eskom, South Africa.

- Eskom Transmission 2003, *Spare transformers and Reactors at Stores and on Site,* TRMASAAI3 Rev 01, Eskom, South Africa.
  Eskom Transmission 2004, *Transformer and Reactor Strategic Spares Policy,* TRMPBVAAVA Rev 01, Eskom, South Africa.
- Eskom Transmission 2004, *Transmission Division Power Transformer Specification*, TECSC009 Rev 0, Eskom, South Africa
- Eskom Transmission 2004, *Transmission transformers Machin Fabrik Reinhausen (MR) Tap changer Modification Instruction*, TRMI0002 Rev 01, Eskom, South Africa.

Table 2.1 is the Tabulation of the causes of severe failures of transformers and the percentage of the different types of failures as a total of the severe failures. This information has been used in conjunction with the standards for transformers in the study.

Transmissions experience with the severe failure of Transformers has been the following

Root cause of failure	**% of total of severe failures**
Windings	60
Tapchangers	20
Bushings	20

Table 2.1: Tabulation of the Cause of Severe Failures for Transformers in Transmission.

Adapted from Eskom Transmission 2007, Life Cycle Management Plan for Power Transformers and Reactors, TBP41-366 Rev 0, Eskom, South Africa.

2.7 Literature Review on Abnormalities on Transformers

Power transformers are the most significant and vital component of the power delivery system. Its reliability and performance remain of great important to the utilities. Irrespective of the failure rate, transformers are also of high concern from the point of asset management. Sudden failure of a transformer may cause an interruption in the power supply thus resulting in high repair costs, revenue losses and environmental as well as collateral damages. Transformers which operate with load and ambient temperatures higher then their design characteristics are prone to acceleration of their ageing process and this also involves the high risk of catastrophic failures (Arshad, Islam & Khaliq 2004, pp.1395 – 1398).

The three dominant factors for accelerating ageing during normal utilization are oxygen, moisture and temperature. Ageing like all chemical processes is accelerated by temperature. The addition of moisture and oxygen compounds thus accelerates the rate of the reactions (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

The first two abnormalities that impact on the Plant Health Status of the transformer is the addition of moisture and oxygen which occurs in transformers where there are extensive oil leaks and corrosion (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

The existence of oil leaks and corrosion results in the introduction of moisture and oxygen from the external environment which decreases the insulation properties of the transformer (oil and paper) and hence reduces the dielectric strength which reduces the flashover voltage (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

This set of events over a period of time reduces the life span of the transformer and results in failure of the transformer (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

Figure 2.3 is a photograph of a transformer at Impala Substation in the East Grid which has experienced oil leaks and is representative of the scenario that has been described and Figure 2.4 is a photograph of a transformer at Athene Substation which has experienced corrosion problems.

Figure 2.3: Photograph of Oil Leaks on a Transformer at Impala Substation in Empangeni

Adapted from 'HVPlant' 2009, CD-Rom, Eskom Transmission, Kwazulu-Natal, South Africa

Figure 2.3 is a photograph of oil leaks on a transformer. These oil leaks form one of the external factors that affect the results of the operations research techniques used in the study.

Figure 2.4: Photograph of Corrosion on a Transformer at Athene Substation in Empangeni

Adapted from 'HVPlant' 2009, CD-Rom, Eskom Transmission, Kwazulu-Natal, South Africa

Figure 2.4 is a photograph of the corrosion on a transformer. These oil leaks form one of the external factors that affect the results of the operations research techniques used in the study.

Whereas oil leaks and corrosion are undesirable, it is not technically justified to spend large sums of money to fix small oil leaks and corrosion problems. Instead means must be found to manage leaks more cost effectively. In new transformers, leaks are already being countered by the specifications to use welded covers, high quality gasket material and O – rings where technically possible. Where ever possible Transmission transformers will have the covers welded to eliminate leaks (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

Serious oil leaks shall be attended to, not only because they threaten the integrity of the transformer but because they also damage the environment. They also raise the need for topping up and that becomes a factor for the availability of oil and the quality of oil as contamination may be introduced (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TBP41-366 Rev 0, Eskom, South Africa).

2.8 Conclusion

Chapter Three, the Literature Review is the research that was carried out on existing and available literature that has been analysed to meet the objectives of the study.

Theoretical knowledge pertaining to the operations research models (simulation and decision tree analysis), mathematical and statistical models for forecasting (moving averages, weighted moving averages, regression analysis and exponential smoothing) and inventory planning (EOQ, re-order point and ABC inventory) was also researched. The technical aspects of the review of Eskom Standards, Procedures, Modification and Technical Instructions was also researched and tabulated.

The literature cited also provided the background on the company, Eskom. This information has been used in Chapters 5 and 6 to analyse the results and to finalise decisions and recommendations. The literature review also focused on two case studies associated with oil leaks and corrosion problems in the East Grid.

The conclusion of Chapter One and Two now provides the foundation for Chapter Three which describes the research methodology that is used for the study.

CHAPTER THREE – RESEARCH METHODOLOGY

3.1 Introduction

Chapter Three is a literature review on the research methodology aspect of the study. The chapter provides existing and available literature on the research methods chosen to conduct the study. A high level overview of the different types of research methods chosen is completed. The process followed to analyse the data used in the research to attain the objectives set out by the research study is also provided.

The reasons for the choice of the quantitative analysis method to carry out the study, the choice of sample size and the information pertaining to the Management Information systems in Eskom was compiled. The chapter explains the foundation for the research topic which is based on the different types of models that were chosen to analyse the secondary data.

The methods are listed as follows: moving averages, weighted moving averages, exponential smoothing, regression analysis (forecasting techniques), simulation, decision tree analysis and economic order quantity (EOQ).

The chapter integrates the different aspects of the research study and indicated what the source of the secondary data is, what the actual secondary data is, the different types of data required to address the objectives of the study and finally the reasons and the different research methods chosen to analyse the data.

The study does not explore the option of using a Questionnaire to obtain data for the purposes of research. The study focuses on the use of secondary data from the Eskom databases.

3.2 Aims of Study

The study focuses on an optimisation model for the management of transformers in the Eskom East Grid system. The study encompasses the use of research models to analyse secondary data pertaining to transformers that are available in Eskom.

The investigation of the processes associated with failure statistics, financial, forecasting of future transformer failures, inventory planning and control for transformer spares and the strategy for the maintenance of transformer tap changer teams has been conducted. The analysis of the data associated with the objectives of the study has been used to investigate the compilation of an optimisation model for transformers.

3.3 Data Collection Strategies

3.3.1 Brief overview of Quantitative and Qualitative Analysis

3.3.1.1 Quantitative Analysis

Quantitative research can be characterized as a linear series of steps moving from theory to conclusions. The measurement process in quantitative research entails the search for indicators. Establishing the reliability and validity of measures is important for assessing their quality. The research can be characterised as exhibiting certain preoccupations, the most central of which are: measurement; causality; generalization and replication. Quantitative research can be subjected to many criticisms by qualitative researchers. These tend to revolve around the view that a natural science model is inappropriate for studying the social world (Bryman & Bell 2007, p.177).

Quantitative analysis is the chosen method of the study. Quantitative analysis has been chosen due to the fact that an objective analysis is done of factual data.

3.3.1.2 Qualitative Analysis

Qualitative research does not lend itself to the delineation of a clear set of steps. It tends to be a more open-ended research strategy that is typically the case with qualitative research. Theories and outcomes are viewed as outcomes of the research process. Action research is an approach in which the researcher and the client collaborate in the diagnosis of a problem and in the development of a solution to the problem based on the diagnosis. It is connected with the method of cognitive mapping (Bryman & Bell 2007, p.436).

3.3.2 Ethical Requirements

Permission has been granted by the Eskom Transmission East Grid Manager, Mr Sifiso Mazibuko for the use of Eskom data for the purposes of the study.

3.3.3 Sample Size

The area for focus chosen for the study is the East Grid in Eskom Transmission in Kwazulu – Natal. The East Grid in Eskom Transmission is situated in Kwazulu - Natal and subdivided into four areas. The Grid consists of various line functions which include Primary (HV) Plant, Secondary Plant and Lines and Servitude. Primary (HV) Plant is responsible for the maintenance for various types of equipment such as transformers, breakers, isolators and switch gear. For the purpose of this study, the plant equipment chosen is transformers.

The sample size chosen is different for the three objectives of the study and is tabulated below:

- For the objective pertaining to the forecasting of future failures of transformers and the development of an inventory management tool, the entire population of transformers for all the Grids in the Transmission network was chosen. The forecasting models could not be done on data pertaining to the East Grid only as there was insufficient data to analyse. The actual data and records was available however upon analysis it was found that there was no or an insignificant number of transformer failures in the East Grid to model on. The study focuses on severe transformer failures and the data in the East Grid was “zero” number of failures for most of the time period of 1996 to 2008. Hence a decision was taken to extend the study to the entire population of transformers in Transmission. The total number of 582 includes 505 transformers and 77 Reactors.

- For the objective pertaining to the investigation of the re-location of the tap changer maintenance team the population of 69 transformers with 56 tap changers was chosen. The maintenance statistics and history for the time period of 1996 to 2008 was used. The sample size chosen was 100% representative of the population of transformers in the East Grid. This taken has been taken as the main objective of the study is to focus on an optimisation model for the management of transformers in the Eskom East Grid Transmission system.

3.3.4. The Overview of Management Information Systems Technology and the Support provided by these Systems to the Business Model and Eskom Transmission Competitive Advance Strategies

The data from the Eskom databases Phoenix, SAP, TIPPS, TAMS, LIMMS and “Eskom HYPERWAVE” have been researched. This data will be integrated and analysed collectively.

3.3.4.1 Overview of Management Information Systems/Technologies used by Eskom

The systems highlighted in blue are currently being used whilst the systems highlighted in yellow are on the plan to be implemented in the future as is illustrated in Figure 3.1.

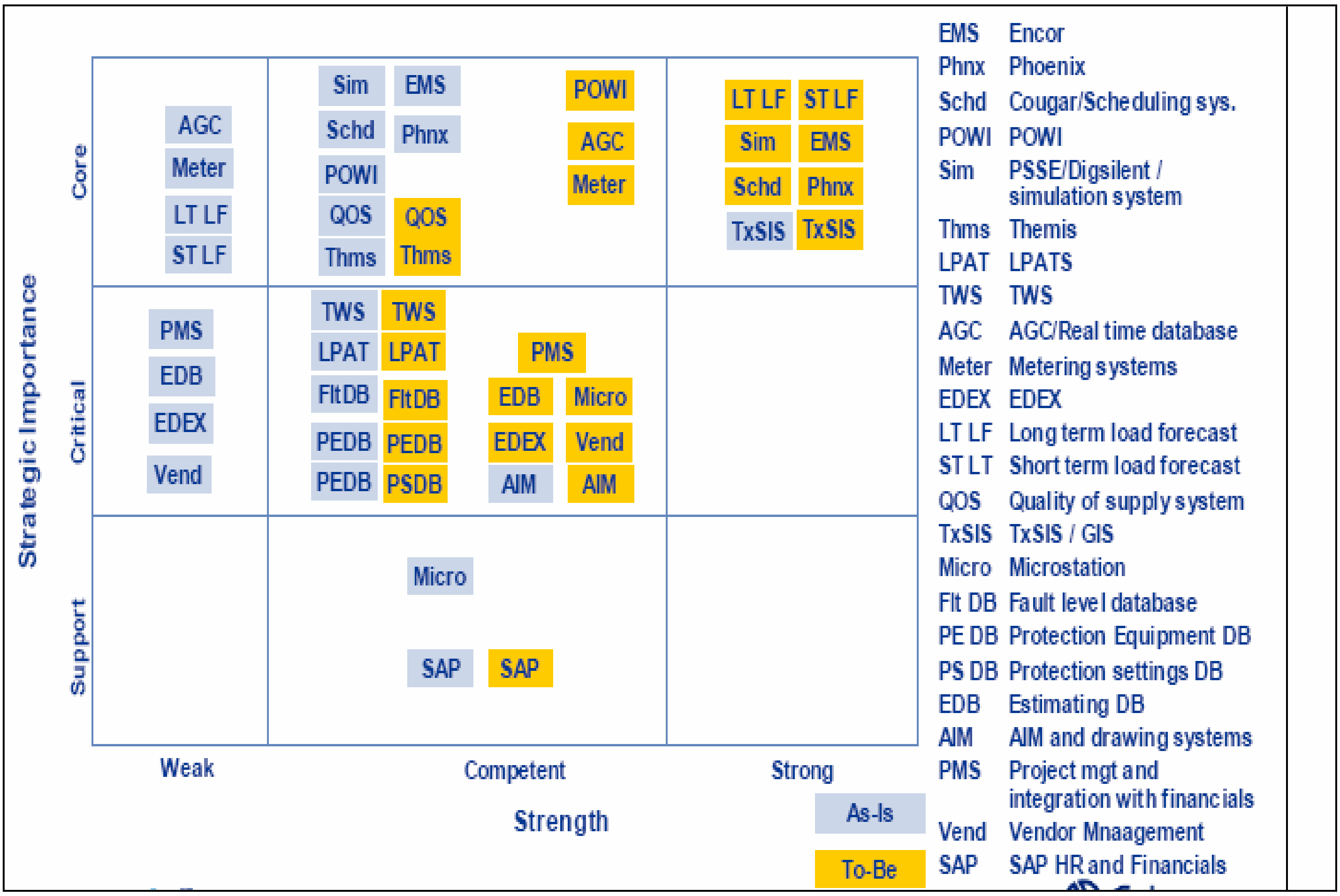

Figure 3.1 Eskom Transmission's Information Systems.

Adapted from "Eskom Management Information Systems" 2007, Eskom Transmission, viewed 06 Sept 2007,

< http://intranet.eskom.co.za/powerzone/main800x600.htm>.

3.3.4.2 Management Information Systems Support for the Eskom Transmission Business Model

Eskom uses various Management Information Systems to capture and process data effectively and efficiently ('Eskom Business Model' 2007, Eskom Transmission, viewed on the 06 Sept 2007, (http://www.eskomdsm.co.za/bussmodel.php>).

Some of the Management Information Systems are discussed below:

- Software development in the aspects of enterprise resource planning (ERP) environments, specifically SAP. This expertise was recently applied in the implementation of the SAP Human Resource modules and the Eskom Transmission Cordaptix billing solution.
- Business continuity management (BCM). Disaster recovery solutions for all Eskom Transmission are being implemented. Eskom is able to implement cost effective BCM solutions that follow the ITIL (Information Technology Infrastructure Library) model. This ensures that the MIS technology is always in line with global best practices.
- Geographic Information System (GIS) is applied to Eskom's asset management and maintenance. System development Support is also provided for the GIS electronic map function used for vegetation management. This enables Eskom to view existing lines and plan for new lines.
- Eskom has implemented new SAP solutions such as SAP e-procurement, SAP Finance for Eskom Enterprises, SAP Plant Maintenance and SAP document management.
- Business process engineering is usually part of every major application development project performed by Eskom.
- Major Information systems include treasury, pensions, plant maintenance, fleet management, plant control, and engineering network schematics

Data centres: most of the equipment is hosted in data centres, one of which is at Eskom's Megawatt Park. A second data centre is located in Doornfontein, Johannesburg and houses most of Eskom's disaster recovery equipment.

3.3.4.3 The Business Benefits of Management Information Systems Support in Eskom

The business benefits are cost savings and increased business value ('Eskom Business Model' 2007, Eskom Transmission, viewed on the 06 Sept 2007, (http://www.eskomdsm.co.za/bussmodel.php>).

- Management Information Systems provide business benefit in the area of cost savings and increased business value - important factors for a cost sensitive organisation.
- Server consolidation and reduction in mainframe usage are two ways in which Eskom reduces costs and improve operating efficiency.
- Another area for cost saving is on desktop support. By using remote desktop management systems, desktops can be accessed and maintained from a central site, resulting in less travelling and fewer support staff. Problems are resolved sooner – resulting in more satisfied clients. Eskom can also download software from a centralised site, making application implementations or upgrades easier. Capacity and asset management is further enhanced.

Governance structures are in place to manage service delivery quality.

3.4 Research Design and Methods

3.4.1 Description and Purpose

The study does not explore the option of using a Questionnaire to obtain data for the purposes of research. The study focuses on obtaining secondary data and analysing it using operations, mathematical and statistical research models. This analysis is then used to address the objectives of the study. It is a quantitative study. Table 3.1 is a tabulation of the different objectives. The figure also tabulates the various operations, mathematical and statistical research models that will be used to address the different objectives of the study.

Main Objective of Study	Objectives for Analysis	Methods for Analysis
Asset Optimisation Model for Transformers in the East Grid in Eskom Transmission	Forecasting of Transformer Failures	Moving averages, Weighted Moving averages, Exponential smoothing, Regression analysis - forecasting Methods
	Re-Location of Tap changer maintenance team	Simulation and Decision tree Analysis
	Inventory Management	Economic order quantity (EOQ)
	Optimisation Model	Integration of all of the aforementioned models

Table 3.1: Tabulation of the various Operations, Mathematical and statistical Research Models.

3.4.2 Analysis of the Data

3.4.2.1 Data for the following aspects is required:

- Data Group One - The specifications of transformers i.e. the area, substation, transformer name, transformer voltage and transformer load.
- Data Group Two – The previous fault history which is the details of transformer trips or failures. This includes the date and cause of the failure. It also includes the action taken which is either that the transformer was repaired or replaced.

- Data Group Three – The history of tap changer maintenance which includes the time period, the cost of maintenance (includes material resources, labour resources and transport costs).
- Data Group Four – The number of severe transformer failures (when the transformer has failed and has to be replaced as it is beyond repair or it has to be removed from site to be repaired in the workshop), the time periods and the costs.
- Data Group Five – The past maintenance history. This includes any planned or abnormal maintenance that was carried out on the transformers.
- Data Group Six – The various maintenance practices, standards, technical instructions and modification instructions that pertain to the transformers.
- Data Group Seven – The financial information plans associated with the different aspects of study. This includes a breakdown of costs of material, labour, transport, lead time and spares.

3.4.2.2 Source of Data for the different Groups

The different data groups that will be sourced have been identified in Section 3.4.2.1 of the study. Table 3.2 is tabulation for the next step.

The table tabulates the different data groups, the source of data from the different Eskom databases. It then provides details of the different operations research models, mathematical and statistical models that will be used to analyse the data. Table 3.2 indicates how this information will be used to achieve the objectives for the study.

Data Group	Source of Data	Methods for Analysis	Objective for Analysis
One	Phoenix	Decision tree Analysis and Simulation	Re - Location of Tap changer maintenance team
Two	Phoenix, TIPPS, TAMS, SAP	Moving averages, Weighted Moving averages, Exponential smoothing, Regression analysis - Forecasting Methods, Simulation, Decision tree Analysis, Economic order quantity (EOQ)	Re - Location of Tap changer maintenance team, forecasting of Transformer Failures and Inventory Management
Three	Phoenix, TIPPS, TAMS, SAP	Moving averages, Weighted Moving averages, Exponential smoothing, Regression analysis - Forecasting Methods, Simulation, Decision tree Analysis	Re - Location of Tap changer maintenance team, forecasting of Transformer Failures
Four	Phoenix, TIPPS, TAMS, SAP	Moving averages, Weighted Moving averages, Exponential smoothing, Regression analysis - Forecasting Methods, Simulation, Decision tree Analysis	Re - Location of Tap changer maintenance team, forecasting of Transformer Failures
Five	Phoenix, TIPPS, TAMS, SAP	Moving averages, Weighted Moving averages, Exponential smoothing, Regression analysis - Forecasting Methods, Simulation, Decision tree Analysis	Re - Location of Tap changer maintenance team
Six	Hyperwave	Decision tree Analysis and Simulation	Re - Location of Tap changer maintenance team, Forecasting of Transformer Failures and Inventory Management
Seven	SAP, Phoenix	Moving averages, Weighted Moving averages, Exponential smoothing, Regression analysis - forecasting Methods, Simulation, Decision tree Analysis, Economic order quantity (EOQ)	Re - Location of Tap changer maintenance team, forecasting of Transformer Failures and Inventory Management

Table 3.2: Tabulation of the data sources and Research Methods

3.5 Conclusion

Chapter Three was a literature review on the research methodology aspect of the study.

The chapter summarised the different types of models that were chosen to analyse the secondary data. The models are listed as follows: moving averages, weighted moving averages, exponential smoothing, regression analysis (forecasting techniques), simulation, decision tree analysis and the economic order quantity (EOQ) model.

The chapter then integrated the different aspects of the research study and indicated what the source of the secondary data is, what the actual secondary data is, the different types of data required to address the objectives of the study and finally the reasons and the different research methods chosen to analyse the data. The study does not explore the option of using a Questionnaire to obtain data for the purposes of research. The study focuses on the use of secondary data from the Eskom databases.

Chapter Three forms the backdrop for Chapter Four and Five. It is the foundation providing the relevant processes and models that has been used in Chapter Four to analyse the data and in Chapter Five to discuss the results of the analysis.

CHAPTER FOUR - RESULTS

4.1 Introduction

In this chapter the various processes to analyse the data for the research study, as was highlighted in Chapter Three, has been completed.

The calculations and the results from the analysis are tabulated in the Chapter.

The first objective of forecasting of future transformer failures was completed using actual data for the entire population of 582 transformers in Transmission. The forecasting methods of moving average, weighted moving average, exponential smoothing and regression analysis was completed.

The second objective of the investigation of the re-location of the transformer tap changer maintenance team was completed using simulation and decision tree analysis techniques.

The third objective of the investigation of an inventory control management system using the actual data for the entire population of 582 transformers in Transmission was completed. This was accomplished suing the economic order quantity model.

The final aspect of the research study which was the investigation and the integration of the aforementioned objectives in order to carry out a preliminary investigation into the suitability of selected operations research techniques for use at Eskom.

4.2 Forecasting of Transformer Failures

4.2.1 Actual Data – Transformer Failures (1996 to 2008)

The transformer failures for all the transformers in Transmission are tabulated in Table 4.1.

Transformer Failures		
No. of Period	Period	Transformer Failures
1	1996	27
2	1997	34
3	1998	28
4	1999	25
5	2000	29
6	2001	28
7	2002	29
8	2003	17
9	2004	40
10	2005	21
11	2006	21
12	2007	16
13	2008	25
TOTAL		340

Table 4.1: Transformer failure data for the time period 1996 to 2008.

Adapted from 'Eskom Performance Reports' 2009, Eskom Transmission, viewed 27 Aug 2009,

<http://txperformance.eskom.co.za/cos_report.php?guest_login=Guest+Login>

The actual data was then forecast using the following techniques:

- Moving averages
- Weighted moving averages
- Exponential smoothing
- Forecasting using regression analysis

4.2.2 Moving average

The moving average is calculated using the following equation:

Moving average = ∑ Most Recent Data / n

Where: Most Recent data = the no. of Transformer Failures

n = number of variables used

In the calculations, a three period moving average was used. This required that the historical data of the last three averages be used to forecast the fourth one. The forecast error and the forecast error squared were then calculated.

In the moving average all the different variables are weighted equally. This is tabulated in Table 4.2 and the graphical analysis illustrated in Figure 4.1, Figure 4.2 and the scatter graph is illustrated in Figure 4.3.

Moving average					
No. of Period	**Period**	**Transformer Failures**	**Forecast**	**Forecast Error**	**(Forecast Error)^2**
1	1996	27	0.00000	0.00000	0.00000
2	1997	34	0.00000	0.00000	0.00000
3	1998	28	0.00000	0.00000	0.00000
4	1999	25	29.66667	-4.66667	21.77778
5	2000	29	29.00000	0.00000	0.00000
6	2001	28	27.33333	0.66667	0.44444
7	2002	29	27.33333	1.66667	2.77778
8	2003	17	28.66667	-11.66667	136.11111
9	2004	40	24.66667	15.33333	235.11111
10	2005	21	28.66667	-7.66667	58.77778
11	2006	21	26.00000	-5.00000	25.00000
12	2007	16	27.33333	-11.33333	128.44444
13	2008	25	19.33333	5.66667	32.11111
TOTALS		**340.00000**	**268.00000**	**-17.00000**	**640.55556**

Table 4.2: Calculations of the Moving average

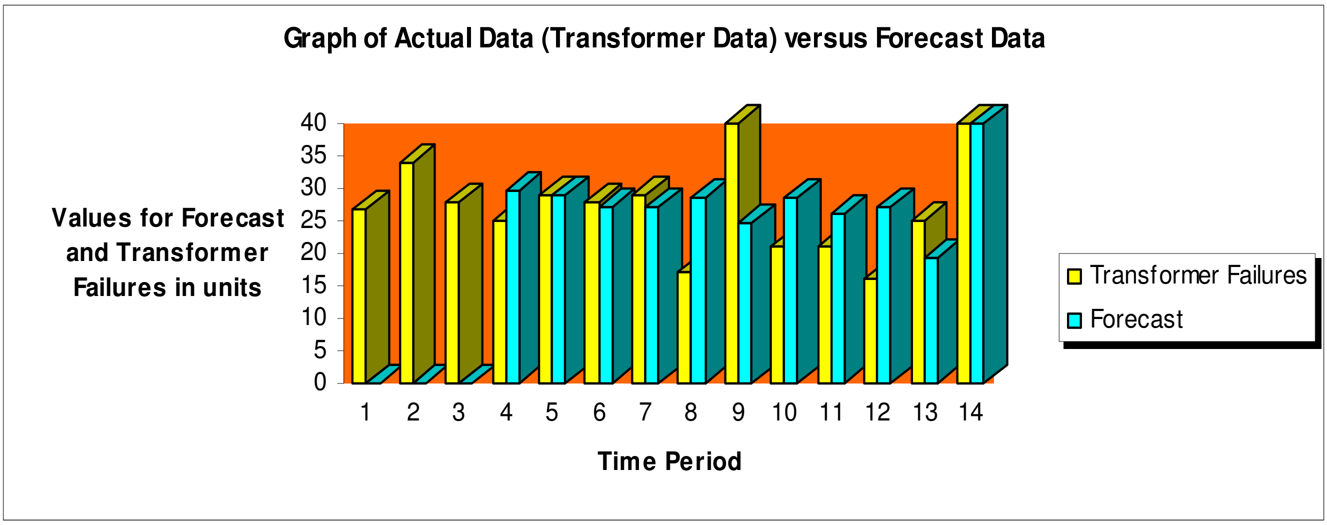

Figure 4.1: The actual data (Transformer failures) versus forecast.

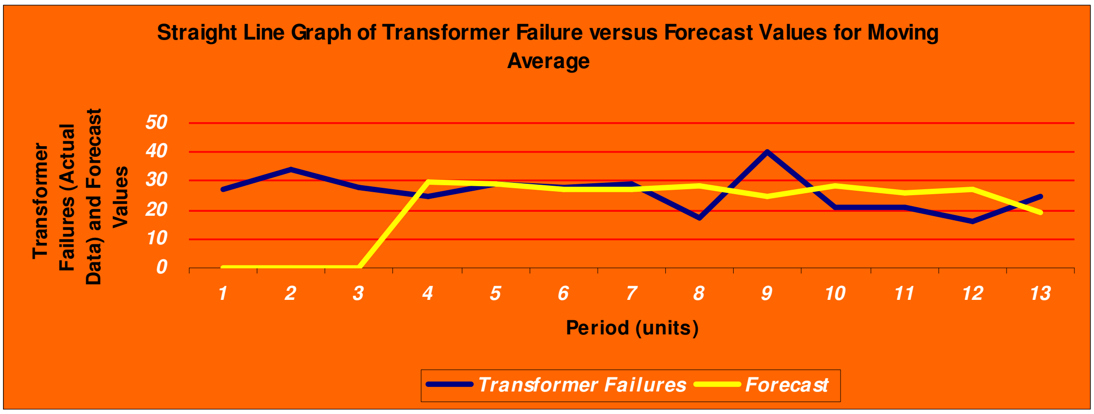

Figure 4. 2: Straight Line Representation of actual data versus forecast data.

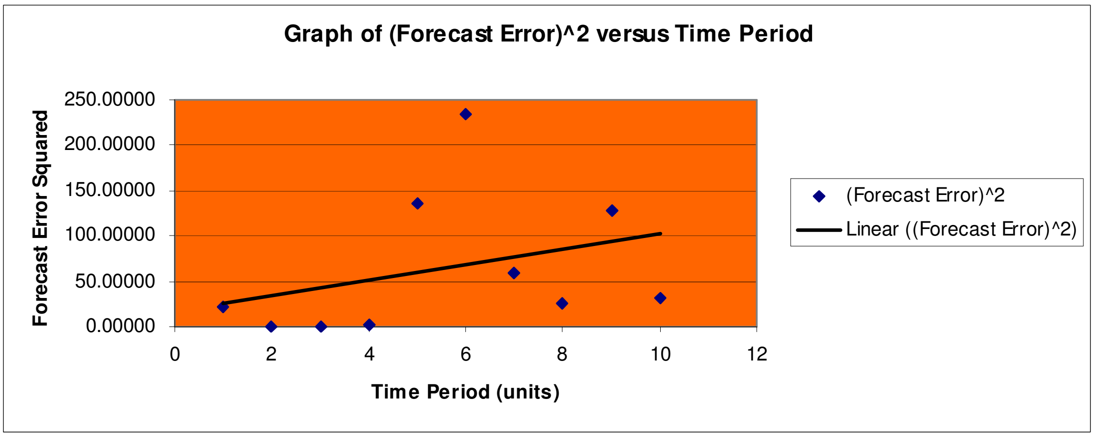

Figure 4.3: Scatter graph representation of the relationship between the forecast error squared calculations and the time period.

4.2.3 Weighted Moving average

The second forecasting method used is the weighted moving average where the data was weighted. The more recent data was given a higher weighting. The further away the data is when it comes to time periods, the less reliable the data is in terms of forecasting. Hence the data for the most recent time periods were given a higher rating. In all other aspects, the calculation of the weighted moving average is similar to the calculations of the moving average.

The calculated weighted average is then used in the moving average equations and the forecast values and forecast errors are calculated. The weighted moving average was calculated using the following equation:

Weighting Moving average = ∑ Most Recent Data / n

Where: Most Recent data = the no. of Transformer Failures

n = number of variables used

Recent Data = Weighted Data Variables

This is tabulated in Table 4.3 and the graphical analysis illustrated in Figure 4.4, Figure 4.5 and the scatter graph is illustrated in Figure 4.6.

Weighted Moving average							
No. of Period	**Period**	**Transformer Failures**	**Weighting of Failures**	**Weighted Average**	**Weighted Moving average Forecast**	**Forecast Error**	**(Forecast Error)^2**
1	1996	27	0.00333	0.09000	0.00000	0.00000	0
2	1997	34	0.00667	0.22667	0.00000	0.00000	0
3	1998	28	0.01000	0.28000	0.00000	0.00000	0
4	1999	25	0.01333	0.33333	0.19889	0.13444	0.0181
5	2000	29	0.01667	0.48333	0.28000	0.20333	0.0413
6	2001	28	0.02000	0.56000	0.36556	0.19444	0.0378
7	2002	29	0.02333	0.67667	0.45889	0.21778	0.0474
8	2003	17	0.02667	0.45333	0.57333	-0.12000	0.0144
9	2004	40	0.03000	1.20000	0.56333	0.63667	0.4053
10	2005	21	0.03333	0.70000	0.77667	-0.07667	0.0059
11	2006	21	0.03667	0.77000	0.78444	-0.01444	0.0002
12	2007	16	0.04000	0.64000	0.89000	-0.25000	0.0625
13	2008	25	0.04333	1.08333	0.70333	0.38000	0.1444
TOTALS		**340.0**	**0.30333**	**7.49667**	**5.594444444**	1.30556	1.704

Table 4.3: Calculations of the Weighted Moving average.

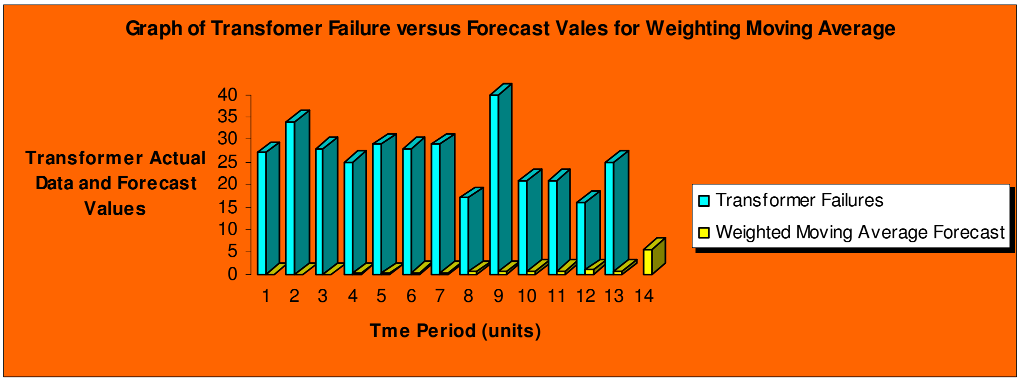

Figure 4.4: Graph of Transformer failures (actual data) versus weighted moving average.

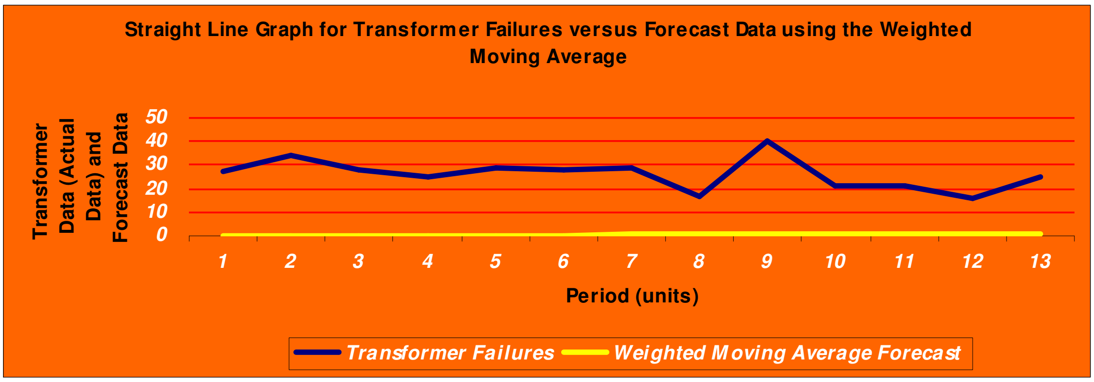

Figure 4.5: Straight line graph representation of Transformer failures versus Weighted Moving average.

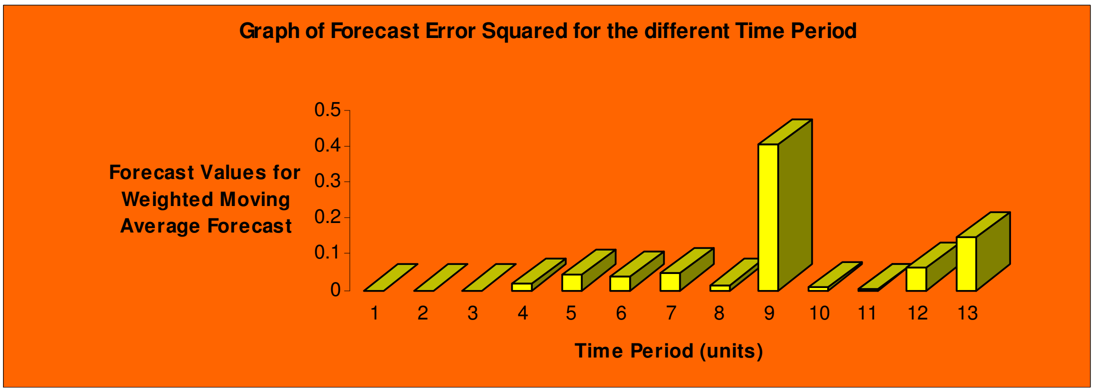

Figure 4.6: Graph of Forecast error squared for the different time periods.

4.2.4 Exponential smoothing

The exponential smoothing is calculated using the following equation:

$$\mathbf{F_{t+1} = \alpha\, Y_t + (1 - \alpha)\, F_t}$$

Where: $\mathbf{F_{t+1}}$ = Forecast of the time series for t + 1

$\mathbf{Y_t}$ = Actual value of the time series in period t

$\mathbf{F_t}$ =Forecast of the time series for period t

$\boldsymbol{\alpha}$ = smoothing cos tan t, $(0 \leq \alpha \leq 1)$

Assume $\boldsymbol{\alpha} = \mathbf{0, 2}$

The calculations pertaining to the exponential smoothing is tabulated in Table 4.5 and the graphical analysis illustrated in Figure 4.6, Figure 4.7 and the scatter graph is illustrated in Figure 4.8.

Exponential smoothing											
No. of Period	**Period**	**Transformer Failures**	**Alpha = 0.2**	**Yt**	**Alpha x Yt**	**(1 - Alpha)**	**Ft**	**(1-Alpha) *Ft**	**Forecast Values (Ft+1)**	**Forecast Error (Yt - Ft)**	**Forecast Error (Yt - Ft)^2**
1	1996	27	0.20	27.00	0.00	0.00	0.00	0.00	27.00	0.00	0.000
2	1997	34	0.20	27.00	5.40	0.80	27.00	21.60	27.00	7.00	49.000
3	1998	28	0.20	34.00	6.80	0.80	28.40	21.60	28.40	-0.40	0.160
4	1999	25	0.20	28.00	5.60	0.80	28.32	22.72	28.32	-3.32	11.022
5	2000	29	0.20	25.00	5.00	0.80	27.66	22.66	27.66	1.34	1.806
6	2001	28	0.20	29.00	5.80	0.80	27.92	22.12	27.92	0.08	0.006
7	2002	29	0.20	28.00	5.60	0.80	27.94	22.34	27.94	1.06	1.124
8	2003	17	0.20	29.00	5.80	0.80	28.15	22.35	28.15	-11.15	124.364
9	2004	40	0.20	17.00	3.40	0.80	25.92	22.52	25.92	14.08	198.204
10	2005	21	0.20	40.00	8.00	0.80	28.74	20.74	28.74	-7.74	59.864
11	2006	21	0.20	21.00	4.20	0.80	27.19	22.99	27.19	-6.19	38.313
12	2007	16	0.20	21.00	4.20	0.80	25.95	21.75	25.95	-9.95	99.038
13	2008	25	0.20	16.00	3.20	0.80	23.96	20.76	23.96	1.04	1.079
91		340		174.00			23.96		23.96	1.04	**582.903**
Total of the Sum of the Different Columns											

Table 4.5: Calculations of Exponential smoothing

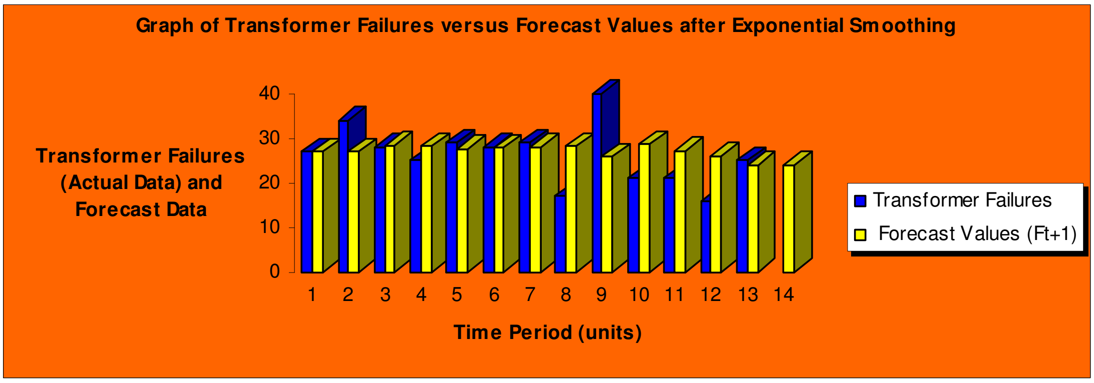

Figure 4.7: Graph of Transformer failures versus forecast value after Exponential smoothing.

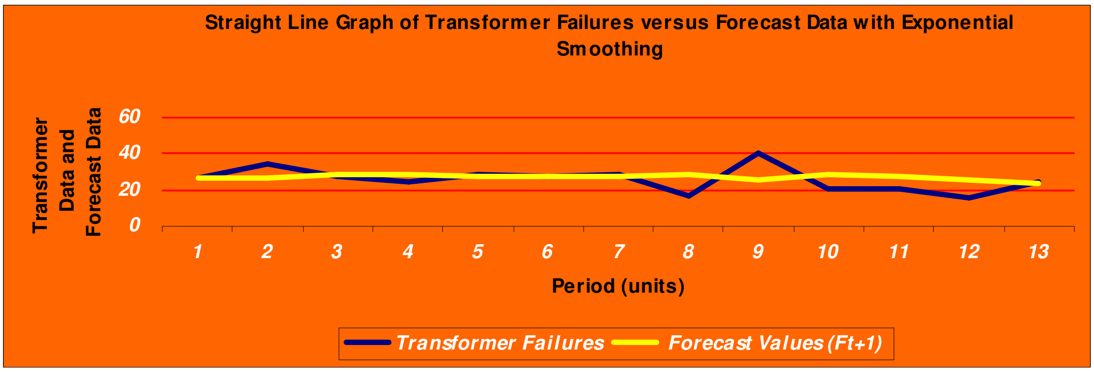

Figure 4.8: Straight line representation of Transformer failures versus forecast values after exponential smoothing.

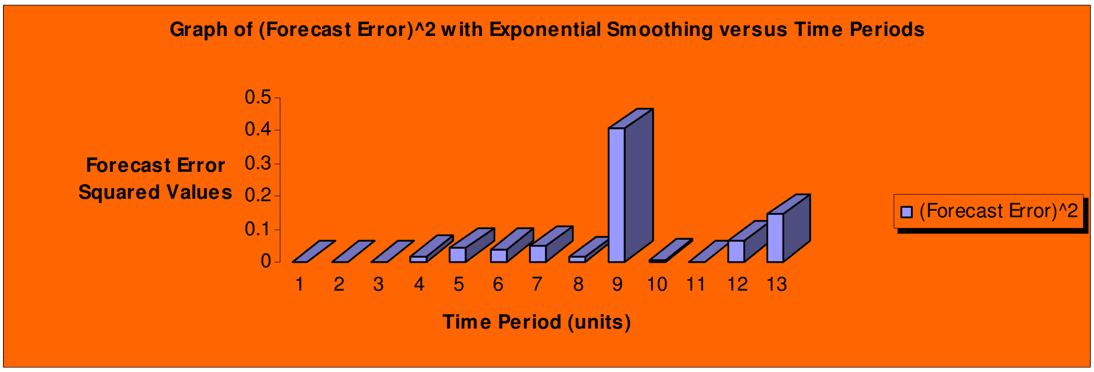

Figure 4.9: Graph of forecast error squared versus time period.

4.2.5 Forecasting Time Series using Regression analysis

The equation of a straight line graph is of the form **y= a + bx,** where

y = equation of a linear graph
a = y-intercept
b = gradient (slope)
x = x-intercept

a + b will determine the number of failures one will expect to have.

$$b = \frac{n\sum xy - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2}$$

a = y – bx is the test for linearity.

Using the equation, b = $\dfrac{n\sum xy - (\sum x)(\sum y)}{n(\sum x^2) - (\sum x)^2}$

$= \dfrac{13(2249) - 91\ (340)}{12(819) - (91)^2}$

$= \dfrac{1703}{2366}$

= 0, 71978 ≈ 0.720

$$a = \frac{\sum y - b(\sum x)}{n}$$

Using equation, a = $\dfrac{\sum y - b(\sum x)}{n}$

$= \dfrac{274.48}{13}$

= 21, 11384615 ≈ 21,114

a = y – bx

By re-substituting into the equation (y = a + bx), one gets:

y = 21,114 + 0,720x

By substitution of the time periods for the value of x, one is able to forecast the number of transformer failures that one expects to have in x years time. The calculations and results pertaining to regression analysis are tabulated in Table 4.6 and is illustrated in Figure 4.10.

Forecasting Time Series Using Regression analysis							
x	y	xy	x^2	y^2	Y=a + bx	Y-y	(Y-y)^2
1	27	27	1	729	19.79	7.21	52.01
2	34	68	4	1156	19.98	14.02	196.45
3	28	84	9	784	20.18	7.82	61.15
4	25	100	16	625	20.38	4.62	21.38
5	29	145	25	841	20.57	8.43	71.03
6	28	168	36	784	20.77	7.23	52.30
7	29	203	49	841	20.96	8.04	64.58
8	17	136	64	289	21.16	4.16	17.31
9	40	360	81	1600	21.36	18.64	347.60
10	21	210	100	441	21.55	0.55	0.30
11	21	231	121	441	21.75	0.75	0.56
12	16	192	144	256	21.94	5.94	35.33
13	25	325	169	625	22.14	2.86	8.18
91	**340**	**2249**	**819**	**9412**	**272.53**	**67.47**	**928.18**
Sum for the different Columns							

Table 4.6: Calculations for forecasting the Transformer failures using Regression analysis.

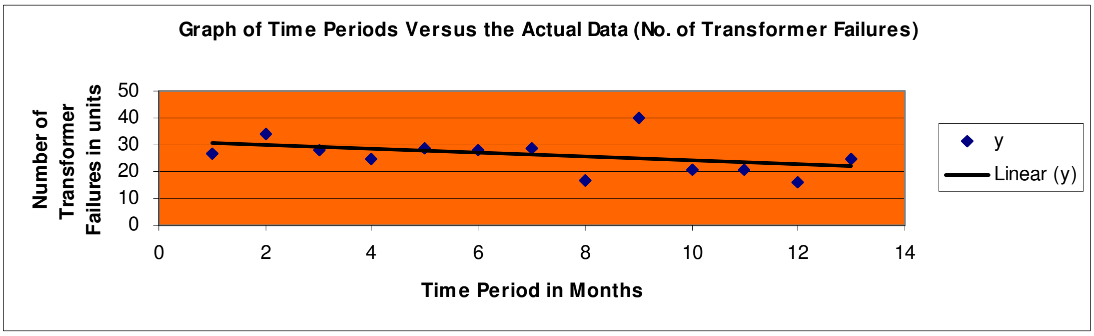

Figure 4.10: Scatter graph analysis for Regression analysis.

4.2.5.1 Calculation of the Standard Error of Estimate

This is calculated by the substitution of the x and y values into the relationship equation to calculate the forecast values. The actual values (no. of transformer failures) are then subtracted from the actual values as indicated in Table 4.6. This is tabulated in Table 4.6 and is extrapolated from the table and shown in Table 4.7.

y	Y=a + bx	Y-y
27	19.79	7.21
34	19.98	14.02
28	20.18	7.82
25	20.38	4.62
29	20.57	8.43
28	20.77	7.23
29	20.96	8.04
17	21.16	4.16
40	21.36	18.64
21	21.55	0.55
21	21.75	0.75
16	21.94	5.94
25	22.14	2.86
340	**272.53**	**67.47**

Table 4.7: Tabulation of Individual Errors

The standard error of estimate is defined by the following equation:

$$S_e = \sqrt{\frac{\sum y^2 - a\sum y - b\sum xy}{n-2}}$$

$$= \sqrt{\frac{9412 - 21{,}114(340) - 0{,}720x2249}{13-2}}$$

= 36,892

Therefore Y = a + b x + ε

Where ε, is the error variable and represents all the variables, measurable and immeasurable, that are not part of the model.

The coefficient of determination is defined by the following equation:

$$r^2 = \frac{a\sum y + \sum xy - n\bar{y}}{\sum y^2 - ny}$$

$$= \frac{21{,}114(340) + 2249 - 13(340/13)\,\hat{}2}{340\hat{}2 - 13\,(340/13)\,\hat{}2}$$

= 0,005017932

Hence r^2 = 0, 005 (rounded off to 3 decimal places)

This means that 0, 5% of variation in the number of employees (y-variable) can be explained by variation in the age of companies (x-variable)

The coefficient of correlation is defined by the following equation:

$$r = \sqrt{\text{coefficient of determination}}$$
$$= \sqrt{0,005017932}$$
$$= 0,071$$

The theory states that the closer the value of r is to 1 then the stronger the relationship between the two variables which include the time period and the number of transformer failures. When r = 0 there is no variation. Since r = 0,071 and is less than 1 but closer to 0, it can be concluded that there is very little or no significant (strong) linear relationship between the time period and the number of failures.

4.3. Assignment of a Tap changer maintenance team using Mathematical and statistical Models of Simulation and Decision tree Analysis

4.3.1 Data pertaining to the List of Transformers and the different types of Tap Changers in the East Grid

The information pertaining to the tap changers was consolidated and is tabulated in Table 4.8.

EAST GRID TRANSFORMER TAP CHANGER TYPES			
CLN	**Plant Description**	**Substation**	**Type**
Pinetown	Ariadne No2 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Ariadne Substation	Reinhausen
Pinetown	Ariadne No3 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Ariadne Substation	ABB
Empangeni	Athene No1 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Athene Substation	Reinhausen
Empangeni	Athene No2 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Athene Substation	Reinhausen
Empangeni	Athene No3 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Athene Substation	Reinhausen
Empangeni	Athene No4 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Athene Substation	Reinhausen
Pinetown	Avon No1 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Avon Substation	Reinhausen
Pinetown	Avon No2 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Avon Substation	Reinhausen
Newcastle	Bloedrivier No1 Trfr Bay 275kV - 88kV - 22kV Trfr TC 275kV	Bloedrivier Substation	Asea
Newcastle	Bloedrivier No12 Trfr Bay 88kV - 22kV Trfr TC 88kV	Bloedrivier Substation	Asea
Newcastle	Bloedrivier No2 Trfr Bay 275kV - 88kV - 22kV Trfr TC 275kV	Bloedrivier Substation	Reinhausen
Ladysmith	Bloukrans No1 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Bloukrans Substation	Reinhausen
Ladysmith	Bloukrans No3 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Bloukrans Substation	Reinhausen
Newcastle	Chivelston Ingagane No1 400kV - 275kV Trfr Fdr Bay 400kV - 275kV - 22kV Trfr TC	Chivelston Substation	Reinhausen
Ladysmith	Danskraal No1 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Danskraal Substation	Asea
Ladysmith	Venus No1 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Venus Substation	Reinhausen
Ladysmith	Venus No2 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Venus Substation	Reinhausen

EAST GRID TRANSFORMER TAP CHANGER TYPES (continued)			
CLN	**PLANT DESCRIPTION**	**SUBSTATION**	**TYPE**
Ladysmith	Danskraal No2 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Danskraal Substation	Asea
Pinetown	Georgedale No12 Trfr Bay 132kV - 88kV - 6.6kV Trfr TC 132kV	Georgedale Substation	Fuller
Pinetown	Georgedale No13 Trfr Bay 132kV - 88kV - 6.6kV Trfr TC 132kV	Georgedale Substation	Fuller
Pinetown	Georgedale No2 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Georgedale Substation	Fuller
Pinetown	Georgedale No3 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Georgedale Substation	Fuller
Pinetown	Georgedale No4 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Georgedale Substation	Fuller
Pinetown	Hector No1 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Hector Substation	ABB
Pinetown	Hector No4 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Hector Substation	ABB
Pinetown	Illovo Nkonka No3 132kV - 88kV Trfr Fdr Bay 132kV - 88kV - 22kV Trfr TC 132kV	Illovo Substation	Asea
Pinetown	Illovo No1 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Illovo Substation	Reinhausen
Pinetown	Illovo No2 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Illovo Substation	Reinhausen
Empangeni	Impala No1 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Impala Substation	Fuller
Empangeni	Impala No3 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Impala Substation	Fuller
Empangeni	Impala No4 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Impala Substation	Asea
Empangeni	Impala No6 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Impala Substation	Asea
Newcastle	Incandu No1 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Incandu Substation	Asea
Newcastle	Incandu No2 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Incandu Substation	Asea
Newcastle	Ingagane No2 Trfr Bay 275kV - 88kV - 22kV Trfr TC 275kV	Ingagane HV Yard	Asea
Newcastle	Ingagane No3 Trfr Bay 275kV - 88kV - 22kV Trfr TC 275kV	Ingagane HV Yard	English Electric
Newcastle	Ingagane No4 Trfr Bay 275kV - 88kV - 22kV Trfr TC 275kV	Ingagane HV Yard	English Electric
Empangeni	Invubu No1A Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Invubu Substation	Reinhausen
Empangeni	Invubu No2A Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Invubu Substation	Asea
Empangeni	Invubu No3A Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Invubu Substation	Asea
Newcastle	Majuba No1 Trfr Bay 400kV - 88kV Trfr TC 400kV	Majuba HV Yard	Reinhausen
Newcastle	Majuba No2 Trfr Bay 400kV - 88kV Trfr TC 400kV	Majuba HV Yard	Reinhausen
Pinetown	Mersey Mpolweni No22 132kV - 33kV Trfr Fdr Bay 132kV - 33kV Trfr TC 132kV	Mersey Substation	Asgen
Pinetown	Mersey No1 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Mersey Substation	Asea
Pinetown	Mersey No12 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Mersey Substation	Fuller
Pinetown	Mersey No13 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Mersey Substation	Reinhausen
Pinetown	Mersey No2 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Mersey Substation	Asea
Pinetown	Mersey No3 Trfr Bay 400kV - 275kV - 22kV Trfr TC 400kV	Mersey Substation	Asea
Newcastle	Normandie No1 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Normandie Substation	Asea
Newcastle	Normandie No11 Trfr Bay 400kV - 88kV - 22kV Trfr TC 400kV	Normandie Substation	Asea
Newcastle	Normandie No12 Trfr Bay 400kV - 88kV - 22kV Trfr TC 400kV	Normandie Substation	Asea
Newcastle	Normandie No21 Trfr Bay 132kV - 88kV - 22kV Trfr TC 132kV	Normandie Substation	Reinhausen
Ladysmith	Tugela No1 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Tugela Substation	English Electric
Ladysmith	Tugela No3 Trfr Bay 275kV - 132kV - 22kV Trfr TC 275kV	Tugela Substation	English Electric
Newcastle	Umfolozi No1 Trfr Bay 400kV - 88kV - 22kV Trfr TC 400kV	Umfolozi Substation	Asea
Newcastle	Umfolozi No2 Trfr Bay 400kV - 88kV - 22kV Trfr TC 400kV	Umfolozi Substation	Asea

Table 4.8: List of Transformers and Tap Changers

4.3.2 Travel Distances for Tap Changer Maintenance Execution

The costs and travel time was consolidated for the different areas and is tabulated in Table 4.9.

Options	Area of Location	Total Cost (Rands)	Total Time (hours)	% Difference in Options to Least Feasible Option	
				Total Cost Diffn %	Total Time % Diffn
A	Pinetown	R839 800	668	12%	10%
B	Empangeni	R803 000	645	16%	13%
C	Ladysmith	R809 400	649	15,5%	12,5%
D	Newcastle	R822 200	657	14%	11,5%
E	Johannesburg	R958 200	742	0%	0%

Table 4.9: Approximate distance and time for travel from area of location for the team to the area where the maintenance is required.

4.3.3 Decision tree representation of Problem

The objective pertaining to the investigation of the re-location of the tap changer maintenance team is analysed using decision tree analysis and this is illustrated in Figure 4.12.

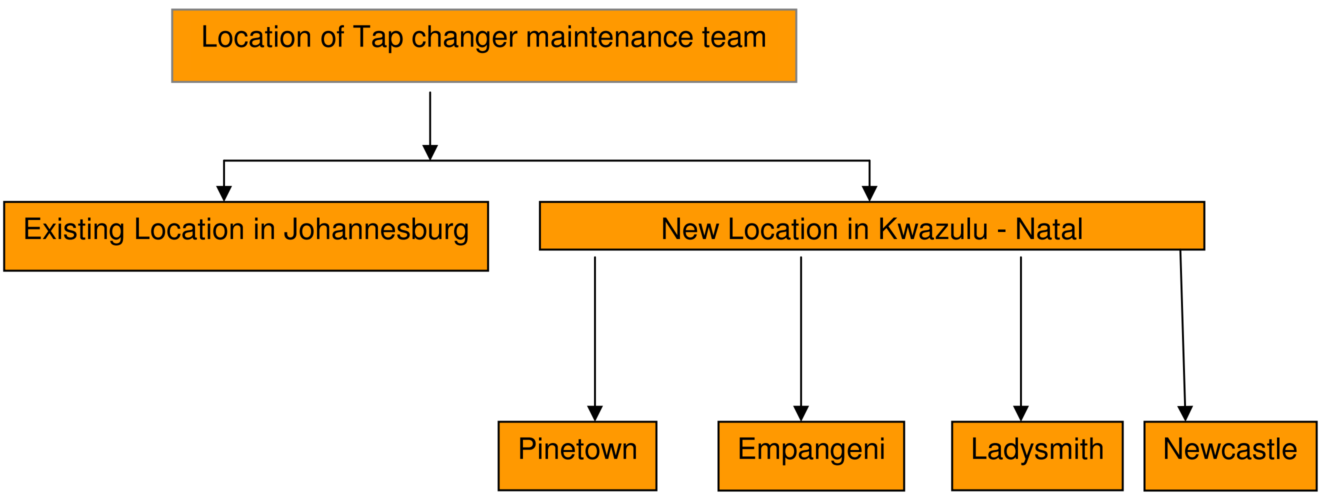

Figure 4.12: Graphical Representation of the Problem using a Decision tree

4.3.4 Simulation of Problem

The total number of tap changers was calculated to be 56. The data in Table 4.10 was then used to calculate the total number of tap changers for the different types.

Tap Changer Types	Number of Different Types
Reinhausen	20
ABB	3
ASEA	20
Fuller	9
English Electric	4
Total of all Types	56

Table 4.10: The total number of the different types of Tap Changers

The location of the different types of tap changers in the different areas in Kwazulu – Natal was then summarized and the probability of occurrence was calculated. This means that the probability of the tap changer maintenance in a certain area was calculated. For example there are 23 tap Changers in the Pinetown area hence the probability of the maintenance is 41 % when compared to the total number of 56. The random number interval was also assigned. The results are tabulated in Figure 4.11.

Location of the tap changer	Frequency	Probability of Occurrence	Random No. Interval
Pinetown	23	41%	0 - 40
Empangeni	8	14%	41 - 54
Ladysmith	8	14%	55 - 68
Newcastle	17	31%	69 - 99
Johannesburg	0	0%	
Total	56	100%	100 numbers

Table 4.11: The frequency of Tap Changer maintenance in the different areas.

There are five different types of tap changers in the East Grid. The probability of the occurrence of a particular type of tap changer eg. ABB was calculated in relation to the total number of tap changers.

The random interval number was assigned to the different types. The maintenance time in hours was also tabulated. This was used to calculate the total cost of labour. The cost of the spares for maintenance on the different types was also listed.

Finally the type of transport required and the cost /km was tabulated in Table 4.12.

Type of Tap Changer	Number of Tap Changers	Probability of Occurrence	Random No. Interval	Maintenance Time (hours)	Cost of Spares	Cost of Labour	Transport Required	Cost/km
ABB	3	5	0 - 4	48	R 15,000	R 40,000	1 x Bakkie & 1 crane	R 16
Reinhausen	20	36	5 - 40	48	R 15,000	R 40,000	1 x Bakkie & 1 crane	R 16
ASEA	20	36	41 - 76	24	R 10,000	R 20,000	1 x Bakkie & 1 crane	R 16
Fuller	9	16	77 - 92	19	R 14,000	R 16,000	1 x Bakkie & 1 crane	R 16
English Electric	4	7	93 - 99	21	R 12,000	R 17,000	1 x Bakkie & 1 crane	R 16
Total	56	100%						

Table 4.12: The probability of occurrence of maintenance on the different type of Tap Changers and associated data related to the cost of spares, cost of labour and travel costs.

Information used for calculations:

- The Total Cost (Rands) is calculated as follows:

  Total Cost (Rands) = Total cost of Travel + Total Cost of Labour + Total Cost of Spares

  where: a) Total cost of Travel (Rands)

  = Travel Time x Cost of Travel per km

where: Cost / km = Cost of Bakkie/km + Cost of Crane /km

= R4/km + R12/km = R16/km

b) Total Cost of Labour = Cost of Labour = 2 employees X rate of R 416 per hour (rounded to the nearest thousand)

c) Total cost of spares = given

- The Total Time (hours) is calculated as follows:

  Total Time (hours) = Total Travel Time + Total Maintenance Time

Duration

where: The total time of travel = return trip

- The distance and the time for travel were allocated in Table 4.9 under section 4.3.3.
- The area in Johannesburg were the team is located is call Rosherville.

Assumptions made:

- Assume that the relocation Cost and Time is zero for the purposes of the assignment.
- Assume that the Living Out Allowance for the purpose of the assignment is zero.

The random number function from Microsoft Excel was used in the simulation for tap changer maintenance for the different types of tap changers in the different areas. A total of 25 simulations were done for the project case. This was calculated as the total of 5 locations x the total of 5 different types of tap changers.

The results for the simulations in the different areas namely Pinetown, Empangeni, Ladysmith, Newcastle and Johannesburg were tabulated in Table 4.13, Table 4.14, Table 4.15, Table 4.16 and Table 4.17 respectively.

Simulation for the Pinetown CLN											
Area of Mntce	Name of Area	Travel Dist (km)	Travel Time (hrs)	Type of Mntce	Mntce Time Duration (hrs)	Cost of Travel per km (Rands)	Total Cost of Travel	Total Cost of Labour (Rands)	Total cost of Spares (Rands)	Total Cost (Rands)	Total Time (hours)
79	Newcastle	700	7.00	58	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
61	Ladysmith	600	6.00	38	48	R 16	R 9,600	R 40,000	R 15,000	R 64,600	54.00
21	Pinetown	200	2.00	34	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
3	Pinetown	200	2.00	74	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
48	Empangeni	400	4.00	88	19	R 16	R 6,400	R 16,000	R 14,000	R 36,400	23.00
26	Pinetown	200	2.00	41	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
27	Pinetown	200	2.00	28	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
82	Newcastle	700	7.00	59	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
17	Pinetown	200	2.00	64	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
73	Newcastle	700	7.00	19	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
82	Newcastle	700	7.00	79	19	R 16	R 11,200	R 16,000	R 14,000	R 41,200	26.00
68	Ladysmith	600	6.00	30	48	R 16	R 9,600	R 40,000	R 15,000	R 64,600	54.00
67	Ladysmith	600	6.00	57	24	R 16	R 9,600	R 20,000	R 10,000	R 39,600	30.00
41	Empangeni	400	4.00	73	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
45	Empangeni	400	4.00	12	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
40	Pinetown	200	2.00	41	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
25	Pinetown	200	2.00	12	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
55	Ladysmith	600	6.00	44	24	R 16	R 9,600	R 20,000	R 10,000	R 39,600	30.00
87	Newcastle	700	7.00	48	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
61	Ladysmith	600	6.00	15	48	R 16	R 9,600	R 40,000	R 15,000	R 64,600	54.00
74	Newcastle	700	7.00	25	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
32	Pinetown	200	2.00	26	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
98	Newcastle	700	7.00	24	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
21	Pinetown	200	2.00	12	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
9	Pinetown	200	2.00	33	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
				Totals :						R 839,800	668.00

Table 4.13: Simulation for the Pinetown CLN

Simulation for the Empangeni CLN											
Area of Mntce	**Name of Area**	**Travel Dist (km)**	**Travel Time (hrs)**	**Type of Mntce**	**Mntce Time Duration (hrs)**	**Cost of Travel per km (Rands)**	**Total Cost of Travel**	**Total Cost of Labour (Rands)**	**Total cost of Spares (Rands)**	**Total Cost (Rands)**	**Total Time (hours)**
79	Newcastle	200	2.00	58	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
61	Ladysmith	400	4.00	38	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
21	Pinetown	400	4.00	34	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
3	Pinetown	400	4.00	74	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
48	Empangeni	100	1.00	88	19	R 16	R 1,600	R 16,000	R 14,000	R 31,600	20.00
26	Pinetown	400	4.00	41	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
27	Pinetown	400	4.00	28	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
82	Newcastle	200	2.00	59	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
17	Pinetown	400	4.00	64	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
73	Newcastle	200	2.00	19	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
82	Newcastle	200	2.00	79	19	R 16	R 3,200	R 16,000	R 14,000	R 33,200	21.00
68	Ladysmith	400	4.00	30	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
67	Ladysmith	400	4.00	57	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
41	Empangeni	100	1.00	73	24	R 16	R 1,600	R 20,000	R 10,000	R 31,600	25.00
45	Empangeni	100	1.00	12	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
40	Pinetown	400	4.00	41	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
25	Pinetown	400	4.00	12	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
55	Ladysmith	400	4.00	44	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
87	Newcastle	200	2.00	48	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
61	Ladysmith	400	4.00	15	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
74	Newcastle	200	2.00	25	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
32	Pinetown	400	4.00	26	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
98	Newcastle	200	2.00	24	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
21	Pinetown	400	4.00	12	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
9	Pinetown	400	4.00	33	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
Totals :										**R 803,000**	**645.00**

Table 4.14: Simulation for Empangeni

Simulation for the Ladysmith CLN											
Area of Mntce	**Name of Area**	**Travel Dist (km)**	**Travel Time (hrs)**	**Type of Mntce**	**Mntce Time Duration (hrs)**	**Cost of Travel per km (Rands)**	**Total Cost of Travel**	**Total Cost of Labour (Rands)**	**Total cost of Spares (Rands)**	**Total Cost (Rands)**	**Total Time (hours)**
79	Newcastle	200	2.00	58	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
61	Ladysmith	100	1.00	38	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
21	Pinetown	500	5.00	34	48	R 16	R 8,000	R 40,000	R 15,000	R 63,000	53.00
3	Pinetown	500	5.00	74	24	R 16	R 8,000	R 20,000	R 10,000	R 38,000	29.00
48	Empangeni	400	4.00	88	19	R 16	R 6,400	R 16,000	R 14,000	R 36,400	23.00
26	Pinetown	500	5.00	41	24	R 16	R 8,000	R 20,000	R 10,000	R 38,000	29.00
27	Pinetown	500	5.00	28	48	R 16	R 8,000	R 40,000	R 15,000	R 63,000	53.00
82	Newcastle	200	2.00	59	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
17	Pinetown	500	5.00	64	24	R 16	R 8,000	R 20,000	R 10,000	R 38,000	29.00
73	Newcastle	200	2.00	19	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
82	Newcastle	200	2.00	79	19	R 16	R 3,200	R 16,000	R 14,000	R 33,200	21.00
68	Ladysmith	100	1.00	30	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
67	Ladysmith	100	1.00	57	24	R 16	R 1,600	R 20,000	R 10,000	R 31,600	25.00
41	Empangeni	400	4.00	73	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
45	Empangeni	400	4.00	12	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
40	Pinetown	500	5.00	41	24	R 16	R 8,000	R 20,000	R 10,000	R 38,000	29.00
25	Pinetown	500	5.00	12	48	R 16	R 8,000	R 40,000	R 15,000	R 63,000	53.00
55	Ladysmith	100	1.00	44	24	R 16	R 1,600	R 20,000	R 10,000	R 31,600	25.00
87	Newcastle	200	2.00	48	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
61	Ladysmith	100	1.00	15	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
74	Newcastle	200	2.00	25	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
32	Pinetown	500	5.00	26	48	R 16	R 8,000	R 40,000	R 15,000	R 63,000	53.00
98	Newcastle	200	2.00	24	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
21	Pinetown	500	5.00	12	48	R 16	R 8,000	R 40,000	R 15,000	R 63,000	53.00
9	Pinetown	500	5.00	33	48	R 16	R 8,000	R 40,000	R 15,000	R 63,000	53.00
Totals :										**R 809,400**	**649.00**

Table 4.15: Simulation for Ladysmith

Simulation for Newcastle CLN											
Area of Mntce	**Name of Area**	**Travel Dist (km)**	**Travel Time (hrs)**	**Type of Mntce**	**Mntce Time Duration (hrs)**	**Cost of Travel per km (Rands)**	**Total Cost of Travel**	**Total Cost of Labour (Rands)**	**Total cost of Spares (Rands)**	**Total Cost (Rands)**	**Total Time (hours)**
79	Newcastle	100	1.00	58	24	R 16	R 1,600	R 20,000	R 10,000	R 31,600	25.00
61	Ladysmith	200	2.00	38	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
21	Pinetown	700	7.00	34	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
3	Pinetown	700	7.00	74	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
48	Empangeni	200	2.00	88	19	R 16	R 3,200	R 16,000	R 14,000	R 33,200	21.00
26	Pinetown	700	7.00	41	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
27	Pinetown	700	7.00	28	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
82	Newcastle	100	1.00	59	24	R 16	R 1,600	R 20,000	R 10,000	R 31,600	25.00
17	Pinetown	700	7.00	64	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
73	Newcastle	100	1.00	19	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
82	Newcastle	100	1.00	79	19	R 16	R 1,600	R 16,000	R 14,000	R 31,600	20.00
68	Ladysmith	200	2.00	30	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
67	Ladysmith	200	2.00	57	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
41	Empangeni	200	2.00	73	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
45	Empangeni	200	2.00	12	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
40	Pinetown	700	7.00	41	24	R 16	R 11,200	R 20,000	R 10,000	R 41,200	31.00
25	Pinetown	700	7.00	12	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
55	Ladysmith	200	2.00	44	24	R 16	R 3,200	R 20,000	R 10,000	R 33,200	26.00
87	Newcastle	100	1.00	48	24	R 16	R 1,600	R 20,000	R 10,000	R 31,600	25.00
61	Ladysmith	200	2.00	15	48	R 16	R 3,200	R 40,000	R 15,000	R 58,200	50.00
74	Newcastle	100	1.00	25	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
32	Pinetown	700	7.00	26	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
98	Newcastle	100	1.00	24	48	R 16	R 1,600	R 40,000	R 15,000	R 56,600	49.00
21	Pinetown	700	7.00	12	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
9	Pinetown	700	7.00	33	48	R 16	R 11,200	R 40,000	R 15,000	R 66,200	55.00
Totals :										**R 822,200**	**657.00**

Table 4.16: Simulation for Newcastle

Simulation for Johannesburg											
Area of Mntce	**Name of Area**	**Travel Dist (km)**	**Travel Time (hrs)**	**Type of Mntce**	**Mntce Time Duration (hrs)**	**Cost of Travel per km (Rands)**	**Total Cost of Travel**	**Total Cost of Labour (Rands)**	**Total cost of Spares (Rands)**	**Total Cost (Rands)**	**Total Time (hours)**
79	Newcastle	400	4.00	58	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
61	Ladysmith	600	6.00	38	48	R 16	R 9,600	R 40,000	R 15,000	R 64,600	54.00
21	Pinetown	1000	10.00	34	48	R 16	R 16,000	R 40,000	R 15,000	R 71,000	58.00
3	Pinetown	1000	10.00	74	24	R 16	R 16,000	R 20,000	R 10,000	R 46,000	34.00
48	Empangeni	1400	14.00	88	19	R 16	R 22,400	R 16,000	R 14,000	R 52,400	33.00
26	Pinetown	1000	10.00	41	24	R 16	R 16,000	R 20,000	R 10,000	R 46,000	34.00
27	Pinetown	1000	10.00	28	48	R 16	R 16,000	R 40,000	R 15,000	R 71,000	58.00
82	Newcastle	400	4.00	59	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
17	Pinetown	1000	10.00	64	24	R 16	R 16,000	R 20,000	R 10,000	R 46,000	34.00
73	Newcastle	400	4.00	19	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
82	Newcastle	400	4.00	79	19	R 16	R 6,400	R 16,000	R 14,000	R 36,400	23.00
68	Ladysmith	600	6.00	30	48	R 16	R 9,600	R 40,000	R 15,000	R 64,600	54.00
67	Ladysmith	600	6.00	57	24	R 16	R 9,600	R 20,000	R 10,000	R 39,600	30.00
41	Empangeni	1400	14.00	73	24	R 16	R 22,400	R 20,000	R 10,000	R 52,400	38.00
45	Empangeni	1400	14.00	12	48	R 16	R 22,400	R 40,000	R 15,000	R 77,400	62.00
40	Pinetown	1000	10.00	41	24	R 16	R 16,000	R 20,000	R 10,000	R 46,000	34.00
25	Pinetown	1000	10.00	12	48	R 16	R 16,000	R 40,000	R 15,000	R 71,000	58.00
55	Ladysmith	600	6.00	44	24	R 16	R 9,600	R 20,000	R 10,000	R 39,600	30.00
87	Newcastle	400	4.00	48	24	R 16	R 6,400	R 20,000	R 10,000	R 36,400	28.00
61	Ladysmith	600	6.00	15	48	R 16	R 9,600	R 40,000	R 15,000	R 64,600	54.00
74	Newcastle	400	4.00	25	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
32	Pinetown	1000	10.00	26	48	R 16	R 16,000	R 40,000	R 15,000	R 71,000	58.00
98	Newcastle	400	4.00	24	48	R 16	R 6,400	R 40,000	R 15,000	R 61,400	52.00
21	Pinetown	1000	10.00	12	48	R 16	R 16,000	R 40,000	R 15,000	R 71,000	58.00
9	Pinetown	1000	10.00	33	48	R 16	R 16,000	R 40,000	R 15,000	R 71,000	58.00
Totals :										**R 958,200**	**742.00**

Table 4.17: Simulation for Johannesburg

4.4 Inventory control and Management Calculations

4.4.1 Calculations of Economic order quantity for Transformers (includes Reactors)

4.4.1.1 Calculation of D

D = Annual Demand in units for the inventory item

= Total number of Transformers to order

= (number of new units required for expansion and planning) **+**

(number of new units required due to the analysis of the failure rate)

Number of new units required due to Expansion

The current Transmission Development Plans 2008 – 2017, indicates that due to unfirm stations, power transfer capabilities and new requirements the following transformers and reactors must be commissioned in the next 10 years (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TPB41-366 Rev 0, Eskom, South Africa). Table 4.18 is a tabulation of this information.

Plant to be installed from 2007 - 2017	Number of units
Transformers >= 250MVA	95
Transformers < 250MVA	30
Total increased installed MVA	63 820 MVA
Reactors	45
Total increased Installed MVAr	11 700 MVAr

Table 4.18: Data pertaining to future commissioning of Transformers

Adapted from Eskom Transmission 2007, Life Cycle Management Plan for Power Transformers and Reactors, TPB41-366 Rev 0, Eskom, South Africa.

From Table 4.18 the total number of new units (transformers and reactors) required for the time period of 2007 to 2017 (10 year time period) is calculated:

Transformers> 250 MVA = 95 units

Transformers< 250 MVA = 30 units

Reactors = 45 units

Total number of new units= 170 units

Hence the total number of new units (transformers and reactors) required due to expansion planning for the future is 170 units. This is calculated over the time period of 10 years. The commissioning rate of the new units is 170 units over a period of 10 years hence the commissioning rate per year is 170/10 = 17 new units per year.

Number of new units required for expansion and planning = 17

Number of new units required due to the analysis of the failure rate

Figure 4.13 indicates 73 failures in a period of 99 months (8, 25 years), or 1 failure every 1, 25 months or 9 failures per year, this evaluated against the present asset base of 505 transformers and 77 reactors, totalling 582 units is a failure rate of 1.5 % per year (Eskom Transmission 2007, "Life Cycle Management Plan for Power Transformers and Reactors", TPB41-366 Rev 0, Eskom, South Africa). The trending of the history pertaining to past transformer failures is illustrated in Figure 4.13.

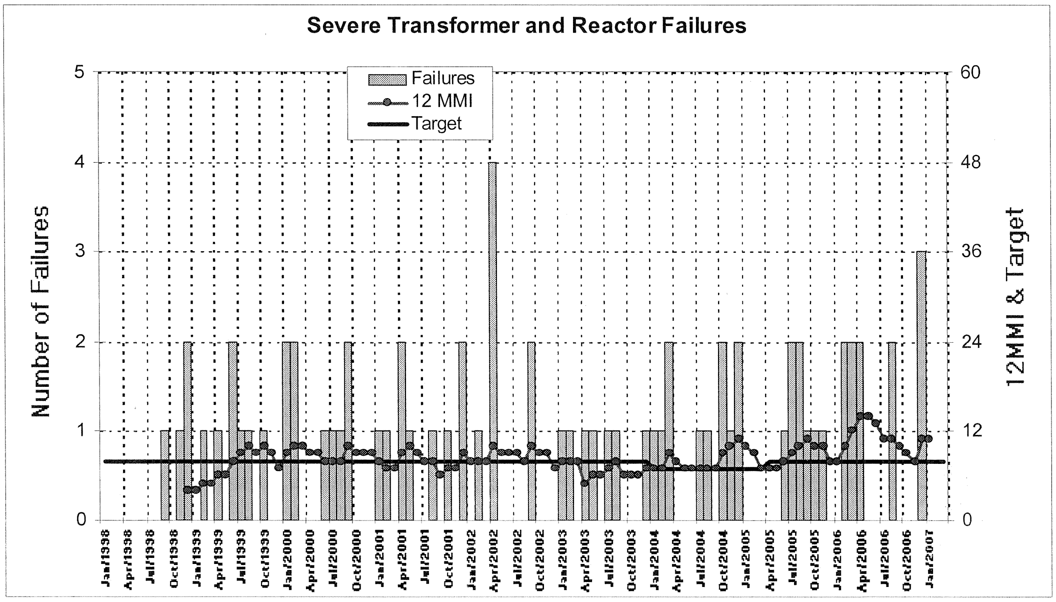

Figure 4.13: Severe Transformer Failures for the time period October 1998 to January 2007.

Adapted from Eskom Transmission 2007, Life Cycle Management Plan for Power Transformers and Reactors, TPB41-366 Rev 0, Eskom, South Africa.

From Figure 4.13, the failure rate is calculated to be 1, 5 % per year (a total of 9 failures per year divided by the total number of transformers (505) and reactors (77) which is 582 units. This past trending is used to plan for the future thus spares will have to be ordered for a total of 9 failures per year.

Number of new units required for due to analysis of the failure rate = 9

Total number of new units required = 9 + 17 = 26

Total number of new units required per year = 26/10 = 2, 6 which is equivalent to 3 units per year.

The value of D is calculated using the following equation:

D = number of pieces to order per year
= Total number of Transformersto order / time period
= 26/10 = 2, 6 ~ 3 units

4.4.1.2 Calculation of Q

The value of Q is calculated using the following equation:

Q = Number of pieces to order
= Total number of Transformersto order pending the storage capacity at stores

The storage areas for spares for transformers in Eskom are the Matla Stores, Rotek stores and locations on site. For the purposes of the study and in order to minimise costs an assumption made is that the only area that will be used for storage is the Mata stores.

Assumptions:

- Storage area is Matla stores
- Total capacity for storage is 10 units.

Q = Total number of Transformers to order pending the storage capacity at stores
= 10

The inventory level is calculated using the following equation:

Average Inventory Level = Q/2
= 10/2
= 5

4.4.1.3 Calculation of the Ordering Costs (C_o) and Holding Costs (C_h)

There is a total of 505 transformers and 77 Reactors in 139 substations operating at voltages of 132kV, 220kV, 275kV, 400kV and 765kV in the Transmission Grids, the combined present value of these machines are about R1, 024 million, with a present replacement value of R6, 965 million (Eskom Transmission 2007, *Life Cycle Management Plan for Power Transformers and Reactors*, TPB41-366 Rev 0, Eskom, South Africa). This information is tabulated in Table 4.20.

MVA	800	667 (1Ø)	500	400	333 (1Ø)	315	250	180 – 120	<100	90.8 HVDC
Number	27	18	66	14	6	50	64	67	167	26

Table 4.20: Transmission Transformers in MVA ratings.
Adapted from Eskom Transmission 2007, Life Cycle Management Plan for Power Transformers and Reactors, TPB41-366 Rev 0, Eskom, South Africa.

This represents an asset base of approximately 125,000MVA, the replacement of this asset base is calculated at R50, 000 per MVA and the repair cost is 70% of this value, resulting in a replacement cost in excess of R6,250 million or if repairable, in a repair cost of R4,400 million. The average age of transformers is just above midlife (20years) as they are at 24, 6 years old (Eskom Transmission 2007, “Life Cycle Management Plan for Power Transformers and Reactors”, TPB41-366 Rev 0, Eskom, South Africa).

From the afore-mentioned information, the costs of replacing the entire asset base of 582 units of 125 000MVA is R50 000 per MVA.

The replacement cost for the entire asset base of 582 units

= 125 000MVA x R50 000 = R6 250 million

The costs for the replacement of 26 units (Demand calculated previously to be 26 units)

= (Demand (units) / total asset base (units)) X Replacement cost of the entire asset base

= (26/582 %) X R6250 million

= R 279 209, 622

~ R279 209, 62

However the replacement costs of the Demand (units/year) = 3 units per year (calculated previously).

Hence the costs for the replacement of 3 units per year

= (3/26%) x R279 209, 62

= R32 216, 49462

~ R32 219, 50

The ordering costs are calculated using the following equation:

Ordering Costs (C_{o}) = ordering cost of each order
= the cost of ordering the required number of units
= R32 219, 50

The ordering costs are calculated using the following equation:

Holding Costs (C_{h}) = holding or carrying cost per unit per year
= 2, 5 % (Eskom policy) X C_o
= 2, 5 % X R32 216 494, 85
= R32 216 494
= R805, 42

4.4.1.4 Economic order quantity

The Economic order quantity is calculated using the following equation:

$$\textbf{EOQ = Q* =} \sqrt{\frac{2DCo}{Ch}}$$

From previous calculations:

D = 3 unit

$\mathbf{C_o}$ = R32 219, 50

$\mathbf{C_h}$ = R805, 42/unit

Therefore:

$$\textbf{EOQ = Q* =} \sqrt{\frac{2DCo}{Ch}}$$

$$= \sqrt{\frac{2x3xR32219{,}50}{R805{,}24}}$$

= 15, 49 units

~ 16 units

The EOQ indicates that the optimum order quantity of 16 units needs to be ordered.

4.4.2 Sensitivity Analysis

The sensitivity of the economic order quantity was calculated by increasing the ordering costs by a factor, which in this case was chosen to be from 2 to 10. The range of between 2 and 10 was chosen randomly. The results are tabulated in Table 4.21.

Increase of Co by Factor	Co	EOQ	% Increase in EOQ
0	R32 219,50	16,000	0
2	R64 439	21,912	141%
3	R96 658,50	26,837	173%
4	R128 878	30,989	200%
5	R161 097,50	34,646	224%

Table 4.21: Impact of the Increase in the Co

4.6 Conclusion

In Chapter Four, the various processes to analyse the data for the research study, as was highlighted in Chapter Three, has been completed.

The calculations and the results from the analysis are tabulated in this chapter and these calculations and results are discussed in Chapter Five. The results from the three objectives namely: the forecasting of future transformer failures, the re-location of the transformer tap changer maintenance team and the investigation of an inventory control management system was completed.

The final objective of the research study which was the investigation and the integration of all the objectives of the study in order to compile an optimisation model for the management of transformers in the Eskom East Grid Transmission system was completed and is discussed in detail in Chapter Five.

CHAPTER FIVE – DISCUSSION

5.1 Introduction

Chapter Five focuses on the discussion and analysis of the results obtained in Chapter Four. The integrated results of all the models used in each objective is discussed in conjunction with the main objective of the study which involves the development of an optimisation model for the management of transformers in the Eskom East Grid Transmission system.

The individual results obtained from the calculations done for the different objectives were discussed. In the objective to forecast future transformer failures, the results from the moving average, the weighted moving average, the exponential smoothing technique and the regression analysis technique were discussed individually and then collectively. The integrated discussion was then used to determine whether the various models could be used in the optimisation model for transformers.

The result from the simulations and decision tree analysis for the objective, of the investigation of the re-location of the transformer tap changer maintenance team was analysed. This discussion was then extended to determine whether these models could be used in the optimisation model for transformers.

The result for the economic order quantity was also discussed for the final objective of the study. The discussion was then done to determine whether this model could be used in the optimisation model for transformers.

5.2 INTEPRETATION OF RESULTS PERTAINING TO FORECASTING

5.2.1 Moving average

The moving average forecast data was plotted against the actual transformer failure data. The interpretation of Figure 4.1 and 4.2 indicates that the forecast figures are 40% of the time period above the actual data, 30% of the time period equal to and less than the actual data. The scatter graph in Figure 4.3

plots the relationship between the forecast error squared results for the different time periods.

5.2.1.1 Identification of Outliers

There are two outliers at time period 5 and 6. These forecast error values can be discarded as it impacts on the x and y values used to compute the gradient in the graph thereby giving an inaccurate trend which can be detrimental during the analysis. The trend line in Figure 4.3 indicates that the forecast error squared is approximately 25.

The sum of the forecast error in Table 4.2 was calculated to be – 17, 00. The trend line in Figure 4.3 may not be perfectly accurate because of the variation in every year. Figure 4.3 indicates that the number of failures has increased over the years. An ideal situation would result in the sum of the forecast data for all the time periods to be equal to 0.

The value of -17 for the forecast error can be attributed to the fact that the failures of transformers are not constant. The Transmission network is dynamic due to factors such as the weather, climate, abnormalities and the network. This results in the accelerated ageing of the transformer which can reduce the life span hence resulting in failure. The transformer's exposure to these different factors varies over various time periods hence resulting in different degrees of ageing.

The moving average technique is the foundation for forecasting and the results must be supplemented with other techniques to obtain a more holistic view of the forecasting for Eskom. It is important to note that the demand for electricity over different periods of time (winter and summer periods), planned maintenance outages, emergency (breakdown) outages and load shedding play in an important role in the forecast values. The demand in winter is greater than in the summer period which requires the increasing of the loading on specific transformers hence "making them work harder". This increases the risks of failures.

5.2.1.2 Additional Factors that Affect forecasting

Other contributing factors include technology, material resources, people resources, skills and spares. These factors all play an important role in efficiency of the system which inevitably results in failures of transformers.
Thus the moving average is the foundation for forecasting. The results of various other forecasting techniques must also be interpreted to make decisions when it comes to forecasting. The external factors affecting the performance of transformers which invariably contribute to their failures must be taken into consideration and worked into the equation to ensure more efficient and effective forecasting.

5.2.2 Weighted Moving average

Figures 4.4, 4.5 and 4.6 clearly indicate that the Forecast values are below the actual data (transformer data) provided. This is due greatly to the fact that the weighting of the data affects the forecasted values. The sum of the forecast error is 1,306 in Table 4.3. The required value for the forecast sum for the forecasting to be 100% accurate is 0. However the value of 1,306 is very close to 0 and is acceptable. Figure 4. 6 plots the forecast error squared for the different time periods. As one can see there is a fluctuation in the values calculated due to the weighting and the actual data provided.

One would use this as a foundation to forecast values by weighting the different data depending on how close the data is to the current period. The data in more recent periods are given a higher weighting due to the fact that the system at that point is time is more or less similar to the system in Eskom in the current time period.

It is important to take note that the forecast error squared for all the time periods with the exception of period 9 and 13 was minimal in comparison to the values for the time period prior to that.

It is important to note that the system in Eskom is a dynamic system which changes all the time depending on the demand of electricity hence it is important to place more emphasis on the more recent data and to give it a higher weighting. This is due to the fact that the current system is more likely to display a similar behaviour to the system a month back in time as compared to 13 months back in time.

Some of the factors that contribute to the higher weighting of data closer to the current time period are the behaviour of plant and equipment, the system network, outages (planned and unplanned), demand, constraints and capacity as illustrated in Figure 5.2.

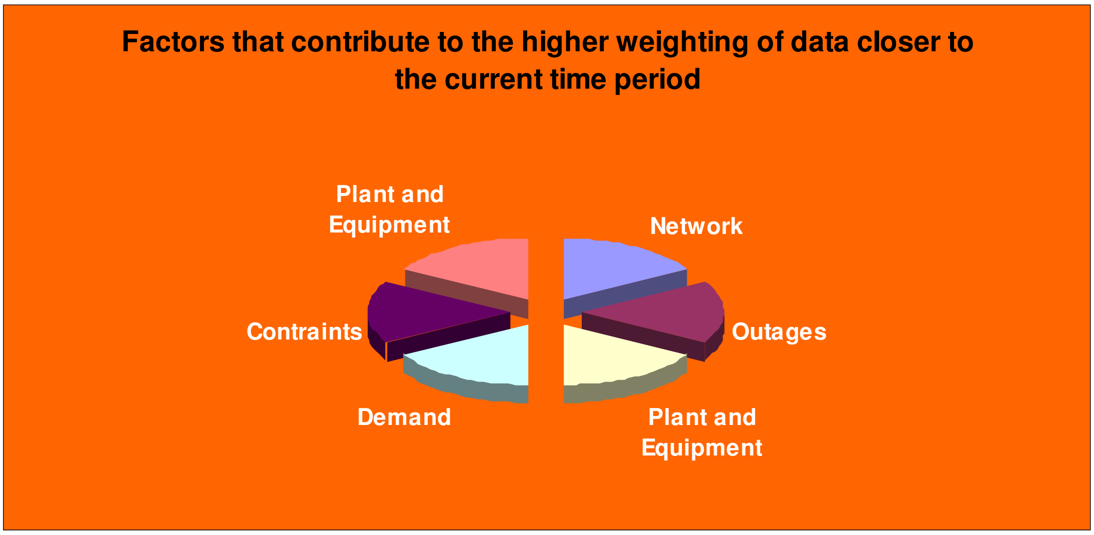

Figure 5.1: Factors that contribute to the higher weighting of data closer to the current time period.

5.2.3 Exponential smoothing

Figure 4. 7 and Figure 4. 8 indicate that the forecast values are higher then the actual data for transformer failures. This is true for all time periods with the exception of time periods 2 and 9. When the actual data for transformer failures was analyzed, it was found that the number of failures in this period decreased. The exponential smoothing equation has removed all fluctuations from the graphs and has provided a synchronized set of forecasted data.

This smoothing technique has not been applied to the actual data hence the fluctuations are still present. The forecast error value is calculated to be 1, 04 as indicated in Table 4 .5. This is more than 0 and the forecast error is acceptable. In Figure 4. 8 there is synchronism between the forecasted data and the actual data in the time periods of 1, 3,5,6,7 and 13. The forecast values obtained from the exponential smoothing technique are the most accurate thus far when compared to those values obtained from the moving average and weighted moving average techniques.

Management decisions will have to take into account that all three different types of variations namely cyclical, seasonal and irregular are experienced, when analysis of Eskom forecasted data is done. In cyclical variation, there are fluctuations in the business cycle due to periods of prosperity, recession, depression and then recovery. This is relevant as consumers use different amounts of electricity in the different time periods. Hence the demand changes and this affects forecasted values. This usually occurs over time periods of longer than a year.

In seasonal variation, the demand for electricity changes during the different seasons in the year. In summer the demand for electricity is less than the demand for electricity in winter. This has been verified by studies of previous data by Eskom. These trends almost repeat themselves each year. Hence management will have to take this into account. When the demand increases, this requires that the existing transformers have to be loaded more than the normal loading and this stresses the equipment which invariably can lead to a failure.

Irregular variation also has to be taken into consideration when forecasting for Eskom. Episodic fluctuations due to bird faults on the lines results in the tripping of the lines and this requires certain transformers to supply more load then they normally do. Hence this also results in stressing the transformers. These are unpredictable but they can be identified. There are also instances were staff maintain the transformers at a very low standard and this results in failures when the transformer is returned to service. These are classified as human errors and incorrect maintenance practices.

Residual variation is also very important and an example of this is the weather. The effectiveness of the weather forecasting has been proved not to be a 100 percent efficient. There have been past occurrences were unpredicted weather conditions have resulted in faulting of equipment and this has resulted in failures.

This analytical statistical method is very important and should be used by management in their forecasting at Eskom. The factors that affect exponential smoothing are tabulated in Figure 5.2.

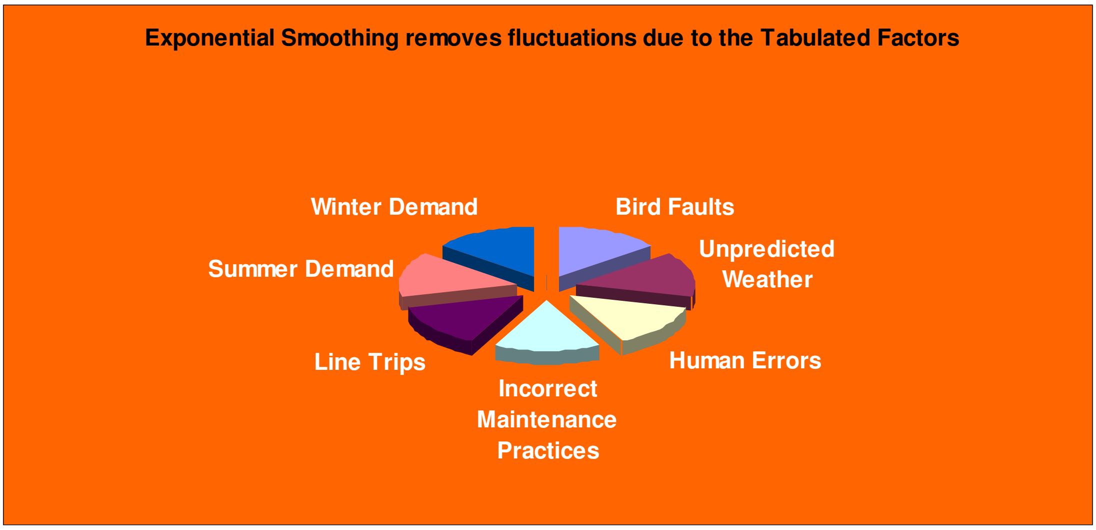

Figure 5.2: Exponential smoothing removes fluctuations due to the tabulated factors.

5.2.4 Regression analysis

The relationship equation (numerical technique) can be compared to the scatter graph plotted in Figure 4.10. If one extrapolates the linear graph downwards it can be seen that the y-intercept is ≈ 21,114. This is in correlation with the predicted equation. Also it can be seen from the predicted equation that the gradient or slope is 0, 720. The positive gradient of the predicted equation is once again confirmed from the scatter graph, where it can be seen that the slope/gradient is positive, whereby the linear graph points towards the right hand side. From the scatter graph in Figure 4.10 above, it has been determined that a positive relationship does exist, i.e. as one variable the (Time Period) increases, then the number of failures increases as well.

The total of the individual errors must be equal to zero, in order to test if the values of x and y are correct. The calculated value from Table 4.7 is -67.47. This is still not equal to 0 hence the determination of the error is then calculated. The standard error of estimate is calculated to be 36,892 and the coefficient of determination is calculated to be 0,071. The coefficient correlation is accepted as it falls within the specified criteria of being any value from -1, 00 to + 1, 00 inclusive. Since r is calculated to be 0,071 there is a perfect positive linear correlation between the two variables. All the data points except for time periods 8, 7 and 12 which lie on the straight line in the scatter graph in Figure 4.10. This also indicates that there is little or no relationship between time and the number of failures.

5.2.5 Comparison Analysis between the Different Forecasting Techniques

It is important to compare the results of the various methods to have a holistic view on the data obtained. The various methods can be compared to make overall decisions on the way forward for the forecasting analysis. Table 5.1 tabulates the mean average deviation for the various methods for the forecasting error and the forecasting error squared methods.

	MAD Forecast Error	MAD Forecast Error^2
Moving average	1,700	2,890
Weighted Moving average	0,1306	0,0171
Exponential	0,087	0,008
Regression	5,190	26,936

Table 5.1: The Mean Average Deviation Figures for the different Forecasting methods

There was correlation between the moving average, the weighted moving average and the exponential smoothing values. However the largest forecast error was on the regression analysis calculations. The smallest error was on the exponential smoothing method.

It is important to note that the moving average, weighted moving average and the exponential smoothing techniques must be used in correlation to interpret the data. The moving average is the foundation for forecasting. This is then built upon using the weighted moving average and the fluctuations are removed by using the exponential smoothing equation. These three methods support the regression analysis method.

The mean deviation error decreases from the moving average to the regression method. The exponential smoothing method has the lowest mean average deviation when compared to the moving average, the weighted moving average and the regression method.

However various other factors must be taken into consideration when forecasting is done. These factors have been explained in detail for the different methods.

5.3 Discussions pertaining to the Re-Location of the Tap Changer Maintenance

5.3.1 Failure Mode of Transformers

Eskom hired the services of a group of International consultants to evaluate the failure mechanism for transformers. The research revealed that 20 % of the failures in Transmission were attributed to tap changer failures. The tap changer failures resulted either in a severe failure or non – severe failure. A severe failure occurs when the transformer has to either be moved from site to the workshop for repairs or the transformer failure cannot be repaired and the faulted unit has to be replaced with a new transformer.

The cost of the project for replacement of a transformer is approximately R35 million for a 250 MVA unit. This cost is based on the Impala Transformer 6 Replacement Project which took place in the East Grid in 2006.

A non – severe failure is classified as a failure which results in a trip (interruption of supply to customers) or forced outage and the situation exists where the transformer has to be repaired on site. This is also a costly exercise which is approximately R2 million. This cost estimate is based on the Georgedale Transformer 12 Project in the East Grid in 2007. In order to prevent severe and non – severe failures it is imperative that tap changer maintenance is carried out as required.

5.3.2 Policy for Tap Changer Maintenance

The policy for tap changer maintenance states that the tap changer must be maintained as per manufacturer's specification or once in three years or every 10 000 operations (whichever comes first).

5.3.3 Problems with the existing Tap Changer Team located in Johannesburg

The tap changers are maintained by a sub – division of Eskom known as Rotek which is located in Johannesburg. The Rotek team is responsible for tap changer maintenance throughout South Africa. Due to this fact the availability of the teams to do work in the East Grid has posed a serious problem as on many occasions the teams have not been available, due to job commitments in other parts of South Africa. The first problem identified with the centralization of the maintenance team in Johannesburg was the availability of the team for the work in the East Grid. The second problem identified was the high cost of maintenance (labour costs and travelling costs).

5.3.4 Decision: Keep Team in Johannesburg or move the Team to Kwazulu - Natal

Due to the problems associated with the availability and the high costs arising due to the centralization of the tap changer team in Johannesburg, the East Grid decided to explore the options of moving the team to Kwazulu - Natal as opposed to keeping them up in Johannesburg. Kwazulu-Natal is subdivided into four areas that include Pinetown, Empangeni, Newcastle and Ladysmith. The feasibility of moving the team to one of these four areas as compared to remaining in Johannesburg was investigated.

5.3.5 Analysis of the Results of the Simulation

The total costs for the tap changer maintenance was quantified by working out the total costs that would be incurred for the team to be situated at the different locations. This was tabulated in Table 5.2.

Options	Area of Location	Total Cost (Rands)	Total Time (hours)	% Difference in Options to Least Feasible Option	
				Total Cost Diffn %	Total Time % Diffn
A	Pinetown	R839 800	668	12%	10%
B	Empangeni	R803 000	645	16%	13%
C	Ladysmith	R809 400	649	15,5%	12,5%
D	Newcastle	R822 200	657	14%	11,5%
E	Johannesburg	R958 200	742	0%	0%

Table 5.2: Summarisation of the total cost and total time for each option considered.

From the table one can deduct that the most expensive option is Option E. The total costs for Option E is R958 000 and the total time is 742 hours. Option B is the most feasible option and costs a total of R809 400 and the total time required is 657 hours. The percentage difference in the total cost of the different options is calculated as a percentage of the most expensive option which is option E.

The percentage difference in the total time of the different options is calculated as a percentage of the most expensive option which is option E. For the most favourable option, Option B, the percentage of the difference in the total cost is 16 % and the percentage difference in the total time is 13%. From these statistics one can conclude that the most feasible option is Option B and this is the chosen option. Hence the tap changer maintenance team will be re-located to Empangeni.

5.3.6 Representation of the Results of the Simulation using the Decision tree

The results from the simulation can now be represented using the decision tree method.

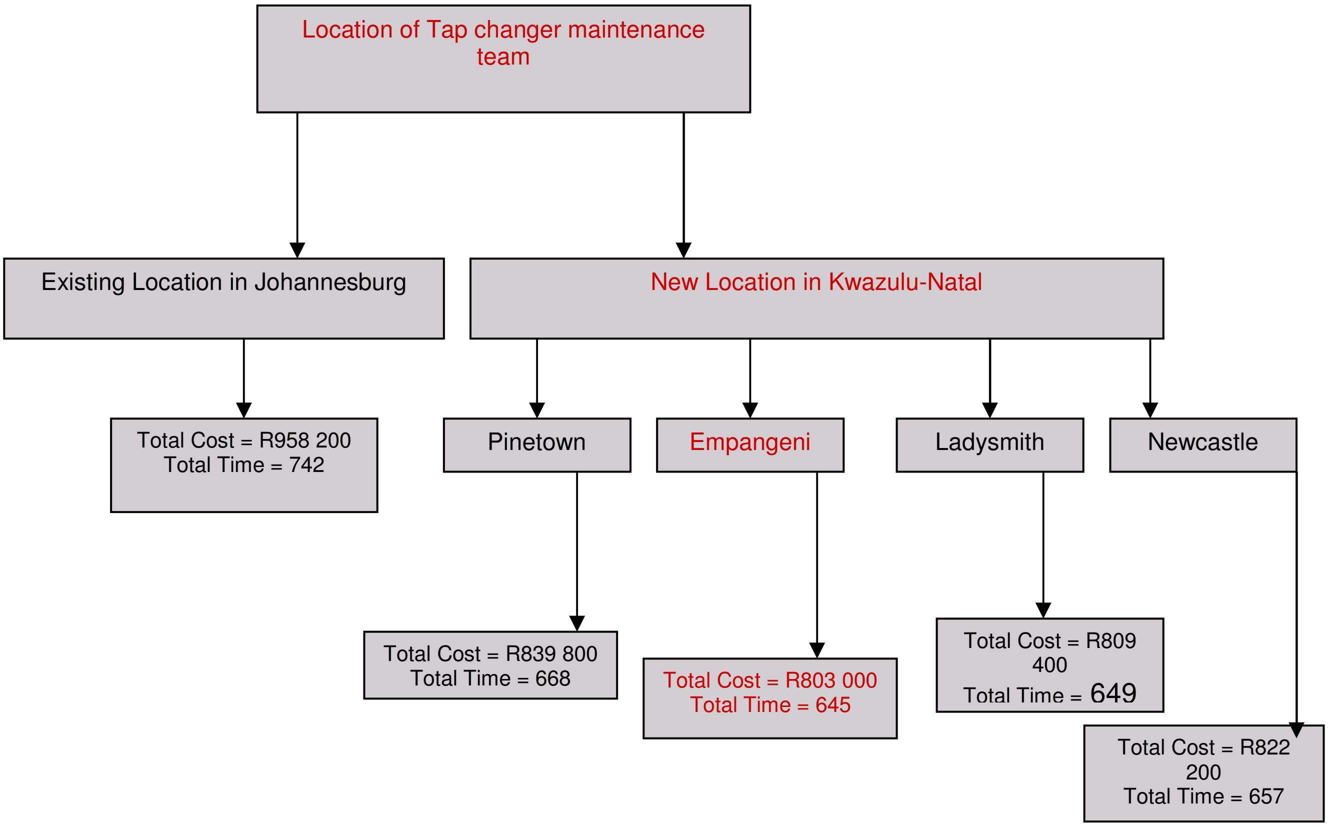

Figure 5.3: Representation of the total costs and total time for the different options using a Decision tree.

The most feasible location for the tap changer maintenance team to re-locate to as indicated by the decision tree analysis is the Empangeni area. The total cost is R803 000 and the total time is 645 hours.

5.4 Discussions on the Inventory and Management Results

One of the key objectives of the study was to develop an inventory and management model for transformers. This was achieved using the economic order quantity (EOQ) model. This tool was used to determine what quantity of transformers should be ordered to be kept as spares. These spares will be used as replacement units for units that have failed and for new units that will be commissioned due to Expansion Planning.

The following assumptions were made during the calculation:

- The demand was calculated to be 3 units per year and was constant.
- The lead time between the placement of the order and the receipt of the order was taken to be constant at 12 months.
- The receipt of the new transformers on order was assumed to be instantaneous and was received at one time.
- Due to great demand for transformers, the suppliers did not provide discounts.
- The only variable costs were the costs of placing the order and the costs of holding.
- The order was placed so that stock outs were avoided completely. If this assumption was not met then there was a great possibility that in the event of a failure of a transformer, Eskom will not be have a replacement which would increase the time duration of an outage on system.

Due to the afore-mentioned assumptions being met, the EOQ was then calculated to be 16 units.

Due to the existence of unfirm stations, power transfer capabilities and the increase in demand for electricity, Eskom computed studies to determine the number of new units that would have to be commissioned. This was calculated to be 170 units in section 4.4.1.1 of this report.

The next reason for the demand of new units and the need for spares was linked to the past failure history of the transformer units in service. The severe – failure history of the transformers for the time period October 1998 to January 2007 was used to determine that the failure rate per year and was calculated to be equal to 9 units. This was calculated in section 4.4.1.1 of this report. The annual demand for the transformers was then calculated by summing these two values and was calculated to be 3 units.

The storage capacity at the stores was then used to calculate the average inventory level of 5 in section 4.4.1.2 of this report. The ordering costs and the holding costs were calculated in section 4.4.1.4 of this report. The economic order quantity was then calculated to be equivalent to 16 units. This indicates that the optimum order quantity of transformers to be ordered is 16 units.

Theoretically speaking this is ideal however the reality of the situation is that the Eskom network is dynamic and is constantly changing. There are numerous factors which contribute to this. The factors that can be controlled such as planned maintenance is not a reason for concern. It is the impact of the non-controllable factors which is of great concern. Some of these factors identified are the weather and environment, abnormalities (defects on the transformers) and faults on the system.

The network system imposes stresses on the transformer in the form of transients and over voltages, emanating from lightning, switching and large through currents caused by faults in the system. This stress impacts on the operation of the transformer and can cause immediate damage to the insulation and accelerate the ageing of the transformer.

Elevated ambient temperatures accelerate both the ageing of the paper and the oil. Temperature has a dominant influence and can be responsible for rapid ageing of paper insulation and oil (components of a transformer) if abnormally high temperatures are reached such as during cooling system failure or significant overloading. The presence of moisture and oxygen increases the chemical activity and accelerates the ageing of the transformer (Auditore 2008, p.2).

These uncontrollable factors contribute greatly to the ageing of the transformer and can result in a severe failure requiring the failed unit to either be repaired or replaced. This will increase the number of failures and hence the economic order quantity model will not be a true representative of the number of spares required.

5.5 Discussions on the Optimisation Model for Transformers in the Eskom East Grid System

The final aspect of the research study, which includes the investigation and the integration of the three objectives of the study in order to investigate the compilation of an optimisation model for transformers. The three objectives include the forecasting of future transformer failures, the investigation of the re-location of the transformer tap changer maintenance team and the development of an inventory control management system.

5.5.1 Optimisation Model using Forecasting Analysis

The results from the forecasting analysis indicated that the moving average, weighted moving average, exponential smoothing and regression analysis models can be used to model the previous failure statistics of transformers in Transmission. These models could not be applied to the failure data of the transformers in the East Grid. This was due to the fact that there was insufficient data to analyse.

The actual data and records were available however upon analysis it was found that there was no or an insignificant number of transformer failures in the East Grid to model on.

The study focuses on severe failures of transformers and the data in the East Grid was "zero" number of failures for most of the time period of 1996 to 2007. Hence a decision was taken to extend the study to the entire population of transformers in Transmission.

The results from the forecasting analysis for the different methods were compared by the calculation of the mean average deviation. There was correlation between the moving average, the weighted moving average and the exponential smoothing values. However the largest forecast error was on the regression analysis calculations. The smallest error was on the exponential smoothing method.

Theoretically it was concluded that the forecasting method can be used to predict future transformer failures which can then be used for planning purposes when it comes to the replacement of transformers and the ordering of spares pertaining to transformers. This tool can be used as part of the optimisation model for transformers which would reduce operational costs and increase profits.

Practically, upon further investigation, it was found that there are many other factors that need to be taken into account. Other contributing factors include technology, material resources, people resources, skills and spares. These factors all play an important role in efficiency of the system which inevitably results in failures of transformers. The external factors affecting the performance of transformers which invariably contribute to their failures must be taken into consideration and worked into the equation to ensure more efficient and effective forecasting.

These factors include material resources, winter demand, summer demand, load shedding, emergency outages, spares, manpower, planned maintenance and technology. It is also important to note that Eskom is a dynamic system which changes all the time depending on the demand for electricity hence it is important to place more emphasis on the more recent data and to give it a higher weighting. This is due to the fact that the current system is more likely to display a similar behaviour to the system a month back in time as compared to 13 months back in time. Some of the factors that contribute to the higher weighting of data closer to the current time period are the behaviour of plant and equipment, the system network, outages (planned and unplanned), demand, constraints and capacity.

Finally all three different types of variations namely cyclical, seasonal and irregular are experienced, when analysis of Eskom forecasted data is done. In cyclical variation, there are fluctuations in the business cycle due to periods of prosperity, recession, depression and then recovery. This is relevant as consumers use different amounts of electricity in the different time periods.

Hence the demand changes and this affects forecasted values. This usually occurs over time periods of longer than a year.

In seasonal variation, the demand for electricity changes during the different seasons in the year. In summer the demand for electricity is less than the demand for electricity in winter. Irregular variation also has to be taken into consideration when forecasting for Eskom. Episodic fluctuations due to bird faults on the lines result in the tripping of the lines and this requires certain transformers to supply more load then they normally do. When the demand increases, the existing transformers are loaded more than the normal loading and this stresses the equipment which invariably can lead to a failure.

There are also instances were staff maintain the transformers at a very low standard and this results in failures when the transformer is returned to service.

Residual variation is also very important and an example of this is the weather. The effectiveness of the weather forecasting has been proved not to be 100 percent efficient. There have been past occurrences were unpredicted weather conditions have resulted in faulting of equipment and this has resulted in failures.

From the aforementioned discussions, it can be concluded that the operations research techniques which include the forecasting methods of moving average, weighted moving average, exponential smoothing and regression analysis can be used at Eskom. However it is important to note that the Eskom system and the environment that transformers operate in is dynamic and has some factors that cannot be controlled. These factors must be taken into consideration when this model is used in the optimisation model. The introduction of these external factors is beyond the scope of this study and is not included in the models.

5.5.2 Optimisation model using Simulation and Decision Tree Analysis

The results of the simulation and decision tree analysis indicated that it was more feasible to re-locate the transformer tap changer maintenance team to one of the areas locally which in this case was worked out to be the Empangeni area. The current stance of locating the team at a central location in Johannesburg is not cost effective.

The simulation and decision tree analysis was done using secondary data that is factually based. The data is purely quantitative and there are little or no significant factors that affect this model. An example of an insignificant factor would be a breakdown of the mode of transport when the team is on route to the required destination to do the maintenance. This would result in a slight deviation in costs and time travelled but this would be minimal and would not affect the model.

The conclusion from the aforementioned discussions is that the operations research techniques of simulation and decision tree analysis can be used as an integral part of the optimisation model successfully.

5.5.3 Optimisation Model using Inventory and Control Management

The economic order quantity was calculated and indicated the optimum order quantity of transformers to be ordered. Theoretically, the economic order quantity can be used to calculate the optimum order quantity of transformers. In addition to this there are various external factors which need to be taken into consideration to finalise decisions when this model is utilised.

Theoretically speaking this is ideal however the reality of the situation is that the Eskom network is dynamic and is constantly changing.

Due to the power transfer capabilities and the increase in demand for electricity, Eskom computed studies to determine the number of new units that will have to be commissioned. The next reason for the demand of new units and the need for spares was linked to the past failure history of the transformer units in service. The annual demand for the transformers is then calculated by summing these two values.

There are numerous factors which affect the operation of the transformer and the system in which it operates. There are factors such as planned maintenance that can be controlled and is not a reason for concern. It is the impact of the non-controllable factors which is of great concern. Some of these factors identified are the weather and environment, abnormalities (defects on the transformers) and faults on the system.

The network system imposes stresses on the transformer in the form of transients and over voltages, emanating from lightning, switching and large through currents caused by faults in the system. The introduction of these external factors is beyond the scope of this study and is not included in the operations research techniques.

This stress impacts on the operation of the transformer and can cause immediate damage to the insulation and accelerate the ageing of the transformer.

Elevated ambient temperatures accelerate both the ageing of the paper and the oil. Temperature has a dominant influence and can be responsible for rapid ageing of paper insulation and oil (components of a transformer) if abnormally high temperatures are reached such as during cooling system failure or significant overloading. The presence of moisture and oxygen increases the chemical activity and accelerates the ageing of the transformer (Auditore 2008, p.2).

These uncontrollable factors contribute greatly to the ageing of the transformer and can result in a severe failure requiring the failed unit to either be repaired or replaced. This will increase the number of failures and hence the economic order quantity model will not be a true representative of the number of spares required.

From the aforementioned discussions, it can be concluded that the operations research technique of the economic order quantity model can be used in the optimisation model. However it is important to note that the Eskom system and the environment that transformers operate in is dynamic and has some factors that cannot be controlled. These factors must be taken into consideration. The introduction of these external factors is beyond the scope of this study and is not included in the models.

5.5 Conclusion

The chapter summarised the discussions pertaining to the utilisation of the various models to develop the optimisation model for transformers. The investigation and the integration of the three objectives of the study were completed.

The three objectives were the forecasting of future transformer failures, the investigation of the re-location of the transformer tap changer maintenance team and the development of an inventory control management system.

It was concluded that the forecasting methods and the economic order quantity model can be used in the development of the optimisation model. However it is important to note that the Eskom system and the environment that transformers operate in is dynamic and has some factors that cannot be controlled. These factors must be taken into consideration. The introduction of these external factors is beyond the scope of this study and was not included in the models.

It was concluded that the simulation and decision tree analysis can be used as an integral part of the optimisation model successfully.

The results in Chapter Four and the discussions in Chapter 5 gives rise to the recommendations and conclusions that will be disclosed in Chapter 6.

CHAPTER SIX – RECOMMENDATIONS AND CONCLUSIONS

6.1 Introduction

The final chapter of the research study includes the recommendations and conclusions that arose from the study. Simple and complex decisions are the key element to a business being successful in the competitively global environment.

The implication of the research on the business and technological environment and the interdependence of these two aspects on one another were discussed. The most important observation from the research study revealed that it is important for technical personnel such as Engineers to have knowledge pertaining to the business aspects of the business in order to make competent decisions. The study has also indicated that it is important for the financial part of the business to have knowledge pertaining to the technical aspect of the business in order to make competent decisions.

The observation and the mitigation strategy for future studies were tabulated. The limitations were identified due to the sample size and secondary data, the source of the secondary data, simulation and decision tree analysis. The limitations of fore-casting was identified and linked to external factors such as load shedding, summer demand, winter demand, material resources, technology, planned maintenance outages, emergency outages, spares, labour resources and skills. These factors were identified as being beyond the scope of this research study and were not included in the models.

6.2 Implications of this Research

High demands on quality of supply, financial resource constraints, ageing of plant and the reduction of maintenance skills have impacted on the importance of transformer maintenance. Within the Transmission Grids there are large power transformers which are the most expensive and strategically important components of any Transmission system. Their presence and operation are indispensable for guaranteeing a faultless power Transmission and Distribution network. Furthermore their loss can only be compensated through enormous financial, technical and operational efforts (Auditore 2008, pp.2 – 9).

On of the most important points to note, is that the research study has integrated the technological and business aspects. The study has also concluded that despite the limitations of the operations research techniques of fore-casting, simulation, decision tree analysis and the inventory control model, these techniques are suitable for use at Eskom to assist in more effective and efficient decision making.

The study has highlighted that it is important for Engineers in Eskom to have knowledge pertaining to the business aspects of the business in order to make competent decisions. It has also indicated that the financial part of the business should also have knowledge pertaining to the technical aspect of the business to make competent decisions.

6.3 Suggestion for Future Studies

The research study gave rise to an array of problems spanning over the actual models used for the study, the secondary data that was used and finally the fact that Eskom is a dynamic environment that is influenced to a great extent by external and internal factors which are both controllable and uncontrollable. Some of the gray areas and problem areas highlighted are tabulated below in this section of the study. The recommendations for future studies are also discussed.

6.3.1 Sample Size and Data

Observation:

The secondary data that was obtained from the Eskom database for the East Grid could be used for the simulation and decision tree analysis models which were used to investigate the objective of the re-location of the tap changer maintenance team. However, the models could not be applied to the secondary data pertaining to the East Grid transformer failures for the forecasting task and for the calculation of the inventory model. The limitation was not the sample size, population or the availability of data but it was in fact the actual statistics. The sample size chosen was indicative of 100% of the transformer population. The data was readily available but the actual number of failures of transformers was too low.

Mitigation:
A decision was taken to apply the forecasting models and the inventory control model to a larger population size which was that of the transformers in the entire Transmission. This now included a larger population and a 100 % of the sample size was chosen. The secondary data pertaining to the number of faults was much higher and could be analysed.

6.3.2 Source of Data

Observation:
The secondary data was obtained from databases such as Phoenix, SAP, TIPPS, TAMS, LIMMS and Eskom Hyperwave. The integrity of the data is dependent to a great extent on the processes that are implemented in Eskom. This includes the actual software and technology used. The introduction of the human element introduces an element of risk associated with the integrity of the data. The integrity of the data is also dependent on the time period that it takes to capture it. The longer the time period, the greater the risk of important data being lost.

Mitigation:
Eskom resources, time and money must be used to support the business's strategy to train and develop employees to an acceptable competency level where the quality of the work performed by the individuals is of an acceptable standard. An extensive amount of resources, time and money is spent on Training. Eskom needs to fast track this process.

There are various time lines that are in place to capture data as soon as an incident occurs. The occurrence of a failure of a transformer gives rise to a preliminary report which must be written and circulated within 24 hours of the failure. An investigation is then carried out in two weeks. Eskom has strict processes in place that ensure that the data captured is of a high quality. Eskom needs to ensure that this process is implemented effectively and efficiently. The processes need to be audited on a regular basis by both internal and external consultants.

6.3.3 Fore-casting in Eskom is Dependent on Various Factors

Observation:

Forecast planning is extremely difficult and is subject to variables such as the load shedding, summer demand, winter demand, material resources, technology, planned maintenance outages, emergency outages, spares, labour resources and skills. These factors results in additional risks due to the fact that transformers are loaded even further and this increases the stress on the equipment. This accelerates the rate of deterioration and contributes greatly to the life span of the transformers. The forecasting model is acceptable theoretically for the analysis of transformer failures but these external factors affect the results that have been calculated.

Mitigation:

Future studies need to investigate the inclusion of these external factors into the study. This will result in an increase in the accuracy of the predictions.

6.3.4 Simulation

Observation:

The simulation pertaining to the re-location of the transformer tap changer maintenance was a time consuming process. It took a very long time period to develop the formulas associated with the different equations used for the simulations. The simulation model was unique and its solutions were not transferable to other problems.

Mitigation:

The mitigation would be the use of more complex software that requires fewer inputs hence reducing the time period to a great extent. Recent advances in software makes it easier to develop simulation models.

6.3.5 Decision tree Analysis

Observation:

The decision tree analysis used to analyze the objective pertaining to the re – location of the transformer tap changer maintenance team was time consuming as all possible alternatives had to be considered before the best one could be chosen. The possibility of not considering an option could have had serious implications on the findings of the research.

Mitigation:

Further studies must investigate the options of different models than can ensure greater accuracy with fewer inputs.

6.4 Conclusion

The main focus of the research study was a preliminary investigation into the suitability of selected operations research techniques for use at Eskom. The objectives of the use of forecasting models to predict future transformer failures, the use of simulation and decision tree analysis to investigation the re – location of the tap changer maintenance team and the use of the inventory model to determine the optimum quantity of transformer spares to be ordered was successfully addressed theoretically.

Hence the conclusion of the research was that all of the aforementioned objectives form part of the optimisation model for transformers in the Eskom East Grid Transmission network.

It was also identified that in the Eskom environment various external factors have to be taken into account when the models are simulated and when the results are analysed. Some of these factors include the network, system constraints, demand, planned and unplanned outages, the weather, climate, bird faults, line trips, incorrect maintenance practices and human errors. The introduction of these external factors is beyond the scope of this study and was not included in the models.

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